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GEOLOGICAL MAGAZINE

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Erosional Patterns and Fracture Zones in Peninsular India

By J. B. AUDEN

ABSTRACT

Three areas in peninsular India are described in which the geometric orientation of the drainage pattern has led to the location of a system of parallel crustal fractures. One area is in the Archaean basement of South India. The remainder are located on Deccan basalts. The fractures are not as a rule accompanied by fault displacements, and are regarded as planes of shearing. The shearing in the Deccan basalts cuts across the post-lava dykes, and is considered to coincide with late magmatic mineralization and the break-up of the Gondwana continent in mid-Tertiary times.

I. INTRODUCTION

THE object of this paper is to describe three areas in peninsular India in which the drainage pattern has been controlled by shear or shatter zones. The origin of the investigation was twofold, one academic, and the other connected with engineering geology, both aspects being undertaken while I was a member of the Geological Survey of India.

Flying over the western Ghats and Konkan early in 1947, it was evident that the Deccan basalts were intruded by large numbers of dykes. This led to an inquiry into the nature of the dykes, both there and in Gujarat and Saurashtra, the results being published in the *Transactions of the National Institute of Sciences of India* in 1949. Subsequent visits to Gujarat, Saurashtra (Kathiawar), and Kutch, have extended the observations.

Again early in 1947, the writer was connected with the foundation conditions of the Mattupatti dam site in the Cardamom Hills of Travancore-Cochin State, where it was found that the river pattern was in part controlled by a system of long and deep shatters. A similar control was suggested from the topographical maps in the geological study of the Vaitarna-Tansa tunnel project adopted by the Bombay Municipality to augment the water supply of the city. The driving of the tunnel established the presence of numerous shatter zones in the

Deccan basalts which had, in fact, been responsible for the disposition of the overlying drainage pattern. These results, together with data from Gujarat, were mentioned in one section of an address to the Section of Geology and Geography during the 38th session of the Indian Science Congress at Bangalore in 1951 (p. 143).

Such a study as is here attempted depends on the accuracy and detail shown by the topographical maps. The greater part of an area of 1·5 million square miles in the former undivided country of India (now India and Pakistan) is covered by 1 in. sheets, partly old-style maps with form-lines often brilliantly true to the topography and geological structure (as for example Kutch), but mainly by modern-style sheets with contours at 50 or 100 feet intervals.

The part of Gujarat along the Tapti river, 180 miles N.N.E. of Bombay City, is covered by old-style maps, some of which show great fidelity to geological influences on topography. A portion of the valley was recently, however, photographed from the air on the approximate scale of 1 : 33,400, in connection with surveys of dam sites, and these photographs have served to emphasize and confirm the deductions implicit in the topographical sheets.

The study of Indian fractures has led to the search for comparable phenomena in other regions, and it is hoped in a second paper to consider the fracture pattern which is known to exist in north-west Scotland.

II. The Problem

The problem, which concerns several areas in India, is to explain the disposition of topographical features, in particular cols, ravines, parts of different river valleys, along extended alignments. These alignments may be either straight or arcuate, but are geometric and not capricious in form. Such a disposition of valleys and cols almost always implies the existence of one of the following geological features—

(1) an easily eroded geological formation
(2) a line of faulting
(3) a shatter zone or line of shearing, with or without displacement
(4) regional jointing, which is generally a consequence of shear stress.

A single alignment, involving parts of one or more rivers, might perhaps be regarded by some as fortuitous, but even one such feature is not likely to be meaningless, and should have a cause that is similarly orientated. Where there is an association of several similar geometric alignments, forming a pattern, it is all the more probable that a regional phenomenon is involved. Where, moreover, the geometric pattern runs oblique to the regional strike of the geological formations, it is

possible to eliminate the first of the alternatives enumerated above, which is perhaps the most potent cause of subsequent drainage.

It may be remarked that faults receive their due treatment from geologists engaged in regional mapping, for these are responsible for abnormal juxtapositions of formations. The mapping of shatter belts and lines of shearing has not often, however, had the same attention, except from a few geologists, of whom Marr was a conspicuous pioneer in Britain, because the field geologist is usually primarily concerned with demarcating formation boundaries and, if these are not displaced, the shatters tend to be overlooked.

It is precisely in such cases that the topography is the principal indicator of directions of weakness, for, although formation boundaries may remain undisplaced, the tell-tale linear association of minor and major depressions is there to provide information.

The indication of the existence of shatter planes should naturally be followed up by actual verification by means of unequivocal geological exposures. This is often very difficult to do. Even in the case of mappable faults, with established shifts in the formation boundaries, all geologists have had experience of the difficulty of finding the contacts of the fault planes, due to the fact that such structures tend to be concealed by weathering products or talus. In general it is the topographical expression which permits the extension of the fault-plane traces beyond the indications originally demanded by local exposures of displaced outcrops. In still greater measure does this apply to shatter belts, where the boundary displacement may be negligible or even nil, and it is a matter of difficulty to decide whether the disturbance seen in any particular exposure is local, or is related to a feature with considerable linear extension. In a speculative matter of this sort it is always possible to object that lines of crustal fracture have been selected which cannot be verified in the field, due to concealment in some regions by alluvium, lochs, or open moor land. Inevitably uncertainties must in many cases exist, but it is considered that the evidence displayed in India, from both good natural exposures and engineering excavations, is sufficiently clear to justify recording, and application to other areas which are characterized by symmetrical dispositions of surface drainage.

III. Joint Patterns in the Vindhyans

That joints certainly exercise some control on the drainage is beautifully displayed from the air in the case of the Vindhyan (Algonkian to Lower Palaeozoic) quartzites of India. The best example of which I am aware is on the Rohtas plateau, 320 miles W.N.W. of Calcutta, around geographical co-ordinates 24° 43′ N.: 83° 56′ E. Three sets of joints, aligned N.E.-S.W., N.N.W.-S.S.E.,

and W.N.W.-E.S.E., have disposed the Kaimur quartzites to be carved out by ravines into triangular blocks, with areas of about 0·15 square miles (0·40 Km.^{2}). The joints cut through the whole 500–700 feet of quartzites and sandstones, but diminish in importance downwards, through the Bijaigarh shales and underlying Rohtas limestone. Individual major joints extend laterally for two miles and tend to be separated by 700 to 1,100 yards. They are not accompanied by faulting or shattering. These joints continue to be abundant further west along the Son valley (*Mem. Geol. Surv. Ind.*, 62, Pt. 2, 1933), and are prevalent also on the Bhainsror plateau 270 miles south-west of Delhi, where they are picked out by lines of shrubs. The jointing doubtless represents reaction to shear stress, and must be taken into account in any comprehensive study of regional tectonics. Their local control over the drainage is clear, but the structures with which this paper are concerned are more extensive, and their influence on the disposition of adjacent rivers is more profound, than anything exercised by simple jointing. It is desirable, therefore, to turn to the areas where the phenomenon of control of drainage by fractures of greater length is best displayed.

IV. Travancore-Cochin

The first area in which the writer became interested is in Travancore-Cochin State, South India, where the rivers flowing through the Cardamom Hills follow straight lines running N.W.-S.E. and N.E.-S.W. The strike of the interbedded Charnockites and para-gneisses is N.W.-S.E., and this is certainly the principal control of the drainage lines in that direction. There is, however, a second direction of river flow, aligned N.E.-S.W., at right angles to the regional strike of the gneisses.

The Mattupatti dam site (10° 7′ N.: 77° 7′ E.) lies on one of these N.E.-S.W. systems. The dam was required to be only 125 feet above bed level, but difficulties were being experienced in the foundations which were attributed by the engineers to the presence of deeper gravels than had been anticipated. Inspection showed that the so-called gravels were in fact rotten pegmatite, and that over a width of 70 feet there were three zones of fracture occupied by clay gouge, chlorite schist, and epidote-chlorite schist. The foundation lay in fact in a major fracture zone, and had to be taken down 130 feet below stream level, deeper than the height of the dam above the original bed. The area has not been mapped in detail and it is difficult from a single short period of inspection to determine to what extent fault displacement had occurred between the two sides of the fracture zone. The general impression gained is that the displacement in the gneisses is not

large. This particular zone is part of a system of rivers, cols and watersheds which is 35 miles long. The height range involved by this system, as indicated by the contoured maps of the Survey of India, is about 6,200 feet, between elevations 800 and 7,000 feet above M.S.L. Consequently, not only are the fractures of great length, but they occur vertically over an exposed height of 6,200 feet, with evident extensions, though of unknown magnitude, to depth.

V. Fractures in the Deccan Traps

(i) *Hyderabad* (*Deccan*).

One of the most striking instances of control of drainage by an extensive fracture and fold zone occurs in Hyderabad, Deccan. The greater part of the Kaddam fracture occurs in crystalline basement, Cuddapah (Algonkian) and Gondwana (Mesozoic) formations, but 30 miles of the north-western part are located on horizontal Deccan basalts. The Kaddam river, 130 miles north of Hyderabad city, follows a straight W.N.W.-E.S.E. course which coincides in different parts with abrupt fold or fault terminations of the Algonkian formations, and with a major fault in the Gondwanas. According to the Hyderabad Geological Survey, partial excavation for a dam site on the Kaddam river has not, apparently, revealed any clearly recognized fault zone, but certain deep pockets in the foundation, located in chlorite schist and retrograde amphibolite, almost certainly do represent a fault feature. In exactly coincident continuation of this Kaddam river alignment of 303°–123°, the drainage of tributaries on the Deccan basalts into the Penganga river around Gadi (19° 33′ N.: 78° 7′ 30″ E.) follow a geometrically straight course. Parallel features to the Kaddam zone exist to the north, which can be traced just south of Pipalgaon and Tamsi.

The coincidence of alignment of all these features cannot be coincidental, but must be due to some controlling weakness, partly folding and faulting, partly probably a shatter zone, which runs for 170 miles across all formations from Archaean upwards to the Deccan lavas. The Deccan-lava fractures are of late Deccan age (Oligocene to Miocene), but these may be rejuvenations of an earlier fracture system in the basement which started in the Mesozoic. It is quite likely, however, that much of the Gondwana faulting was of Tertiary age, and possibly contemporaneous with the major faulting that let down the Gawilgarh and Narmada troughs in the Deccan basalts (*Proc. Nat. Inst. Sci. Ind.*, 15, p. 326, 1949). For further evidence regarding the probable nature of the fractures in the Deccan lavas of Hyderabad it is necessary to turn to the Konkan area, 50 miles north-east of Bombay city.

(11) *Konkan* (*Text-fig.* 1).

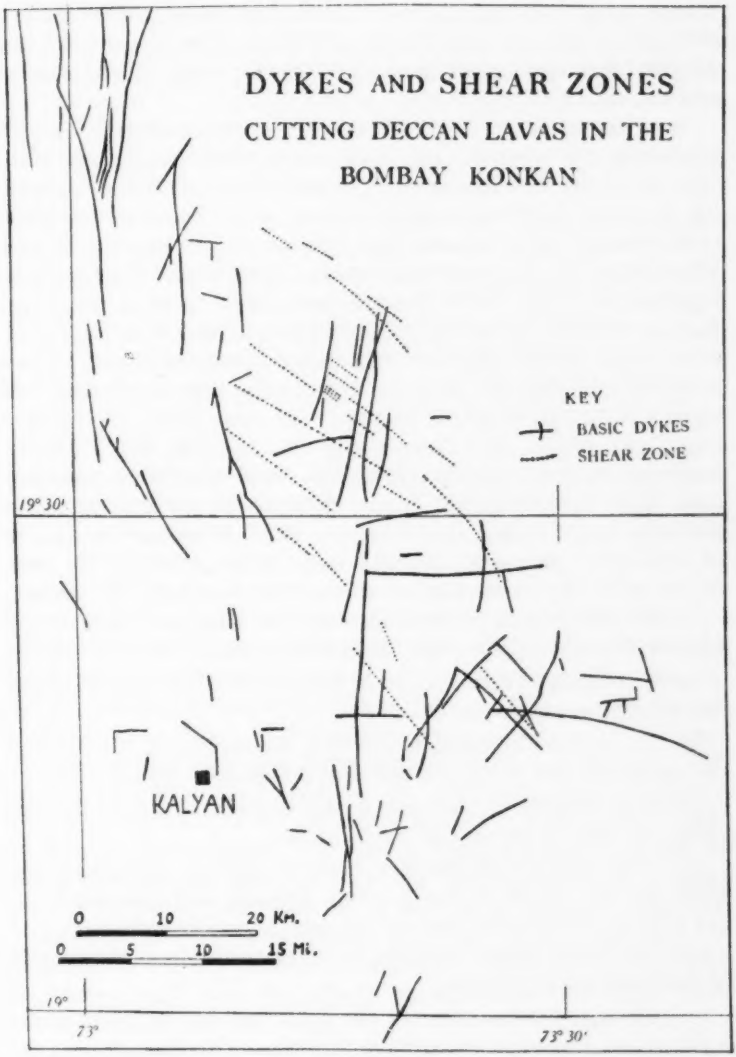
The Konkan first aroused interest in 1947 on account of the striking basic dykes which cut the Deccan basalts (1949, plate ix). They show prominently from the air as long narrow ridges, a few of which are up to 300 feet in height above the numerous sub-plateau levels. The majority are well demarcated on the 1 inch to 1 mile topographical sheets of the Survey of India with 50 feet contours. These dykes vary in width from a few feet to over 300 feet, and consist of dolerite and olivine dolerite. A few remarkably straight gullies are also seen from the air, in particular that which crosses the Kalu River at 19° 20′ N. : 73° 19′ E. in a N.W.–S.E. direction. This could be interpreted either as a fracture zone, or as a dyke which gives negative relief because of greater ease of weathering. Experience in Gujarat and Central India suggests, however, that the dykes of all compositions away from large rivers stand up as ridges, and that it is only in the beds of major rivers, along which heavy monsoon discharges with velocities of the order of 10 feet per second pass, that the whole or parts of the great basic dykes are excavated by abrasion below the levels of the contiguous basalts.

Further east, on the main plateau and flanking precipices, as close to Ratangarh 4255 Hill (19° 30′ N.: 73° 43′ E.), deep erosional gullies are manifest from the air striking N.W.-S.E. and cutting through at least 1,000 feet of lavas. These have not been visited on the ground, and although they appear to be major fractures rather than mere joints, some ambiguity must remain until they are examined closely.

In the Konkan, as in Hyderabad Deccan, many of the streams follow a W.N.W.-E.S.E. course, flowing towards either W.N.W. or E.S.E. across horizontal lavas. Examination of the topographical sheets suggested control by fractures, such as a prominent line which passes through Tansa for 12 miles and crosses three local watersheds, but clear evidence for the nature of the postulated fractures was not until recently available.

Fortunately, the Bombay Municipality has had to increase its water supply by constructing a dam on the Vaitarna River. Water from the reservoir thus formed will be led through three sections of a tunnel totalling 20,400 feet in length, to the existing Tansa reservoir. Part of the tunnel-system had already been lined with concrete before it was possible to visit it, but, through the courtesy of Mr. N. V. Modak, Special Engineer, and Mr. P. P. Dani, Construction Engineer, of the Bombay Municipality, assistance was readily given to examine 9,000 feet of the south-western part of the tunnels, orientated N.N.E.–S.S.W., running close to hill 839 (19° 38′ N. : 73° 16′ E.).

Unfaulted, flat-lying, lavas are traversed in the tunnels by a system



TEXT-FIG. 1.

of mainly vertical W.N.W.-E.S.E. veins occupied by clay gouge, horses of basalt, and vertical stringers of calcite, quartz, and zeolites. The greatest thickness of any single shatter zone is 17 feet, between chainages 18185 and 18202 measured on the south-east side of the

tunnel. Other gouge seams of only 2 inches are present, but the average thickness of the observed fractures is 2½ feet. Out of the 8,937 feet of tunnel that were logged, there are 30 fracture zones, with an average spacing, therefore, of 300 feet.

According to the engineers, 603 feet of the tunnel concrete lining were reinforced, the reinforcement being in the zones occupied by clay-filled fractures. This represents 3 per cent of the length of the tunnel, but is not an exact representation of the actual combined thickness of the fracture zones, because reinforcement tended to overlap beyond the extent of the clay gouge veins into the sound basalt. The measured aggregate thickness of the fracture zones in the part of the tunnel that was unlined amounts to 75 feet, or 0·84 per cent of the length that was logged. No evidence for fault displacements was found. Overbreak was considerable in some of the wider clay zones, and roof cavities in the two widest, of 10 and 17 feet, were large. The fracture zones were seldom leaky, even during the monsoon, which may be attributed to sealing by the clay gouge. More often leaks developed from joints in the adjacent basalts close to the fractures, and it is probable that the clay in the fissures acted as vertical barriers to ground-water movement, diverting water accumulating in the zone of saturation along open clay-free joints in the basalt into the tunnels.

Certain points may be stressed about the fractures found in the tunnels, and inferred elsewhere from gullies in the surface topography:

(*a*) No significant displacement of the lava flow in which the tunnel was driven has been observed.

(*b*) No vertical displacement is seen in the surface scarp outline of the successive lava flows, exposed over hundreds of square miles.

(*c*) No horizontal displacement is seen in places where the fracture zones cut through the vertical basic dykes.

(*d*) It has been argued elsewhere (1949, p. 145) that the basic dykes which cut the basalts in the Konkan, Gujarat, and Saurashtra are not feeders to the lavas, but are in general post-lava, belonging to a later hypabyssal phase. Since the fractures cut the dykes, they would be later even than the dykes.

(*e*) Although the fractures cut the dykes, one set of dykes in the Konkan lies parallel to the fracture direction. This suggests that the couple stresses, which were originally responsible for the triangular pattern of fractures and dyke intrusion, continued subsequently to be relieved by fracturing in one direction only.

(*f*) The presence of secondary hydrothermal mineralization, in the form of calcite, quartz, and zeolites, within the fractures indicates that the mineralization, and probably also the formation of the fractures, took place during a late magmatic episode in the Deccan

igneous cycle, the planes of fracture being the avenues up which mineralizing solutions of the waning volcanic activity migrated.

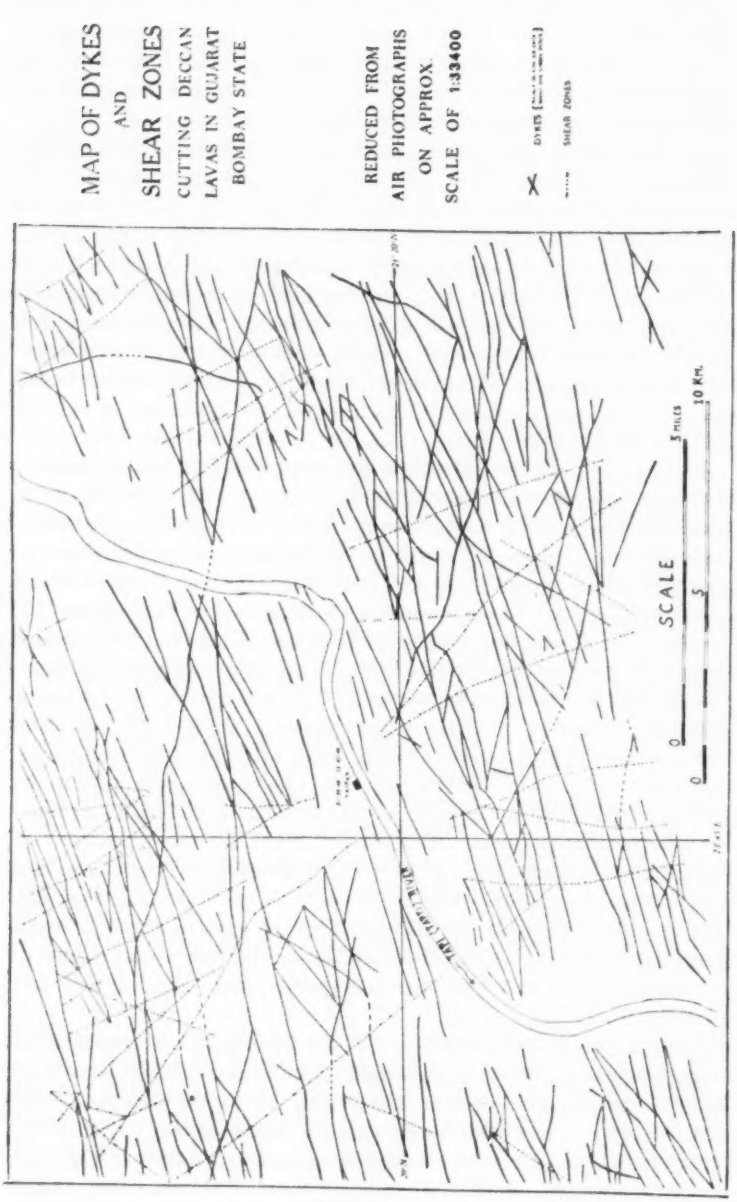
(*g*) It is necessary to look for stresses which resulted in no significant displacements, but which nevertheless caused considerable shattering. These are interpreted as shear fractures.

(*h*) The spacing of the fractures in the Vaitarna-Tansa tunnels averages 1 : 300 feet. This is much closer than the spacing of the overlying surface drainage pattern which occupies and follows the same W.N.W.-E.S.E. direction. Every fracture zone is not in fact represented on the surface by a gully. But every major stream and gully running in this direction may be regarded as owing its course to the existence of a single wide fracture zone, or to a combination of smaller parallel fractures close enough together to behave as a larger unit, and to influence surface erosion and the direction of run-off.

(iii) *Gujarat* (*Text-fig.* 2).

Various reservoir projects have been considered on the Tapti (now Tapi) river in Gujarat, about 180 miles N.N.E. of Bombay City, in an area of slightly folded Deccan lavas which is traversed by clusters of basic dykes (1949, p. 132). As in the Konkan, the dykes show up magnificently from the air, and have been studied in some detail in connection with the investigation of dam sites at Kakarapar (21° 16′ N. : 73° 22′ E.) and Ukai (21° 15′ N. : 73° 36′ E.). The major dykes, between 100 and 300 feet in width, are dolerites, with or without olivine, and having specific gravities of 2·95 and 3·05. Some become gabbroic in texture. Their general trend is E.N.E.–W.S.W., and they are abundantly manifest between north latitudes 21° 00′ and 21° 45′ and east longitudes 73° 15′ and 74° 40′. One major dyke, cutting the 74° east longitude at 21° 23′ north latitude, can almost certainly be followed for 80 miles. The smaller dykes are more generally of fine-grained basaltic type. They cut the dolerites and are themselves severed by minor cross faulting, as well as by horizontal shearing. The horizontal shearing has slightly offset the vertical basalt dykes at Kakarapar, and has effected a lamination parallel to the plane of movement which was very clearly exposed before the barrage was constructed.

Our main concern is, however, with the vertical fracture zones which form prominent gullies and ravines orientated N.W.-S.E. on both sides of the Tapti River east of Mandvi. The most striking is that which controls the geometrically straight course of the Karjan River for a distance of five miles through co-ordinates 21° 32′ : 73° 34′, and probably extends north-westwards to near Rajpipla, and south-eastwards to the Tapti River 3½ miles downstream of Vajpur village, over a distance of 35 miles.


MAP OF DYKES
AND
SHEAR ZONES
CUTTING DECCAN
LAVAS IN GUJARAT
BOMBAY STATE
REDUCED FROM
AIR PHOTOGRAPHS
ON APPROX.
SCALE OF 1:63400
DYKES
SHEAR ZONES
SCALE
5 MILES
10 Km.

TEXT-FIG. 2.

The interesting point about these fractures is that, even more clearly than in the Konkan, they cut through the basic dykes without any horizontal displacement or off-setting. A few cases are seen on the aerial photographs in which one set of dykes has apparently been shifted by another, although it would be difficult without further field study to be sure that more than one period of dyke intrusion is actually involved. Two shear-fractures along different plane directions do not necessarily cross each other in plan at a single point, but may show offsetting without any difference in the time of formation of each fracture being involved. Where offsetting occurs in dykes of identical material, such as the olivine-dolerite and the gabbroic dykes so prevalent in Gujurat, it is probable that intrusion along both sets of fractures was simultaneous. The fractures about which this paper is primarily concerned, present in straight gullies with pronounced negative relief in contrast to the dyke ridges, cut right across the dykes without any displacement. Clear examples are to be found in the following three localities:—

(*a*) 21° 17′ 30″ N.: 73° 50′ 17″ E.
(*b*) 1,450 yards east of trig. point 764 (21° 18′ 30″ N.: 73° 48′ E.)
(*c*) 21° 22′ N.: 73° 44′ E.

The exposed vertical height range of the fractures is about 500 feet, but there is no doubt that they extend to considerable depths in the crust. They are clearly analogous to the Konkan shatters which likewise control the surface drainage, and have been verified in tunnel exposures. In Gujarat the fracturing is mainly vertical, but horizontal zones have been found at one dam site.

VI. A Comparable Fracture Zone in the Garhwal Himalaya

In interpreting the Deccan fractures a case may be cited of a major fracture zone exposed during the excavations of the Marora dam site, on the Nayar tributary of the Ganges (29° 59′: 78° 38′). The dam site is located on monotonous slates and quartzitic slates of the Simla Slate series, and occurs about 3,000 feet below the major Garhwal thrust plane (1937, p. 423). The slates are cleaved at an angle markedly oblique to the bedding, and a system of vertical joints parallel to the river was noticed. But no indications of any major fault zone were apparent, either at the dam site itself, or in the cliffs downstream thereof where the river makes a right-angle bend. Yet exploration by means of tunnels and diamond drilling revealed that a major shatter zone was present, concealed below talus on the left abutment, which dipped S.W. at a steep angle into the abutment on that side. The true thickness of this zone of completely shattered slates and clay gouge varied from 50 to 80 feet. Detailed mapping by

S. P. Nautiyal on the scale of 1 : 600 of the slightly different colour variations in the Simla Slates subsequently indicated that they may have been a horizontal shift of about 150 feet between the two sides of the fault zone. (1951, p. 134.) Here then is a major weakness, of critical importance to the stability of the dam, which it was estimated would cost £750,000 to repair in foundation treatment, and yet gave such little surface indication of magnitude. On the other hand, the Garhwal thrust, which lies structurally above the Simla Slates, and has resulted in a horizontal translation of some 50 miles, often produces clean-cut contacts that, in the case of certain juxtapositions of similar lithological types and grades of metamorphism, might to the unwary be mistaken for a normal sedimentary succession. The Marora river fault, with a gouge and shatter zone varying from 50 to 80 feet in width, has produced a very small displacement, but extremely large local shatter effects. The movement was possibly oscillatory, and the total aggregate distance travelled between two points on opposite sides of the fault plane may have been considerable. But the net displacement is small.

VII. Conclusions Regarding the Deccan Fractures

The Marora fracture zone has been cited because, although it occurs in a geologically very different terrain, characterized by major overthrust dislocations, it yet presents features which appear to be in common with those of the Deccan lava plateau. It is thought that the mainly N.W.-S.E., or W.N.W.-E.S.E. fractures cutting the Deccan basalts have arisen with little or no net displacement. Whether or not oscillatory movements took place along them is difficult to state, but, since there is no sign of either offsetting of the dykes, by horizontal movements, or vertical displacement of the horizontally bedded lavas, it is considered improbable that much oscillation occurred. It would indeed be too much of a coincidence that the opposite sides of the fractures should always have returned to their former original positions. Yet it is necessary to account for the clay gouge and basalt horses so common in the Konkan fractures, and it must be assumed that intense stress, and probably stress reversals, occurred between the crustal blocks. The fractures are thus regarded as simple shears, rather than as normal or tear faults. They have involved some 100,000 square miles of the Deccan plateau, and extend downwards into the crystalline and pre-Tertiary basement. The whole system may be considered as related to Gondwana trough faulting, and break up of the Gondwana continent towards the close of the Deccan igneous cycle, in front of the Himalayan orogen.

The phenomenon is of interest in its magnitude, and because of an apparent relationship with similar features in north-western Scotland

which it is proposed to discuss in a subsequent paper. In a more speculative vein, it is possible to go further and consider the broadly radial relationship of many of the river courses in western India relative to the plutonic masses of Saurashtra.

The principal alignments of the Narmada and Tapi Rivers are directed towards Junagadh. These rivers flow westwards, and their catchments show a deep embayment into the generally eastward flowing rivers of the peninsula. On the other hand, the headwaters of the Godaveri, Ghod, and Bhima flow radially away from the Saurashtra centres. It is true that their watersheds lie far to the south-east of Saurashtra, on the top of the Deccan plateau, but it should be remembered that the drainage pattern and directions of the peninsular rivers has been much altered in relatively recent times, when it is thought that the Panvel flexure, and synclines of the Gulfs of Cambay and Kutch, developed. It is suggested that, before late-Tertiary folding had occurred to modify the watersheds and directions of flow, the river system of western India may have been in part controlled by radial fracturing which was related to Kathiawar where, alone in the whole of the great area of Deccan basalts, occur the three unique plutonic centres of Ranpur, Junagadh, and Chamardi-Chogat.

SUDAN GEOLOGICAL SURVEY,
P.O. BOX 410,
KHARTOUM.

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An Arenig Volcanic Series near Charlestown, Co. Mayo.

By W. A. Cummins

Abstract

A graptolite fauna, found in cherty shales interbedded with volcanic rocks south of Charlestown, Co. Mayo, indicates an Arenig age.

An inlier of Lower Palaeozoic rocks occurs a few miles south and east of Charlestown. The rocks within the inlier consist of an Ordovician volcanic series and a Silurian sedimentary series. This area was mapped and described by the Geological Survey of Ireland, the greater part of the inlier being on sheet 76 (Wilkinson and Cruise, 1874), and the rest on sheet 65 (Symes, Wilkinson, and Kilroe, 1881). Fossils were collected from the Silurian.

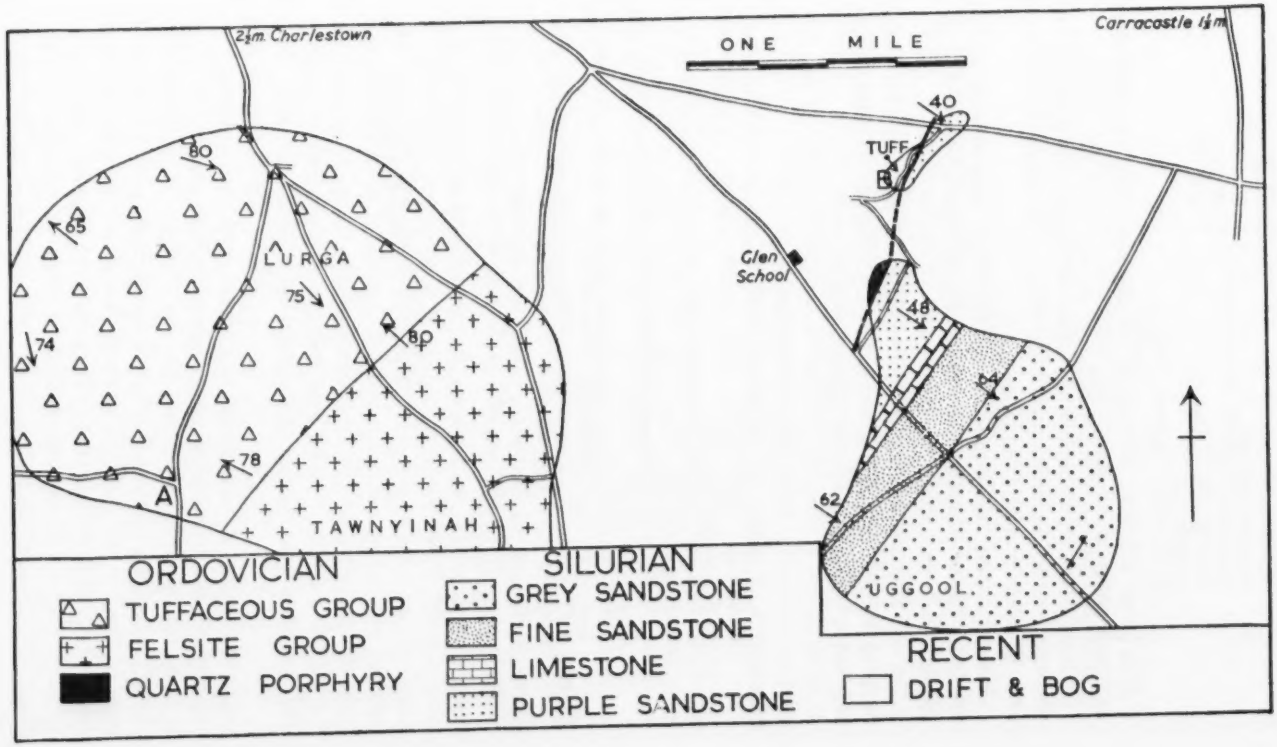
Kilroe (1897, p. 71) found "double graptolites" in black shales associated with cherts, felsites, and volcanic rocks. He compared the volcanic rocks with those occurring west of Lough Mask, about 30 miles to the south-west, and considered them to be of Bala age.

The Silurian succession, over 6,000 feet thick, is shown on the map. The sequence seems to be conformable throughout, and current-bedding, chiefly in the purple sandstones, shows that it is uninverted, contrary to the opinion of the Survey Officers (Wilkinson and Cruise, 1874, pp. 14, 22). The Silurian beds dip away from the Ordovician, but the nature of the junction is uncertain: the only exposure, east of Glen School, shows a faulted contact.

The Ordovician is best exposed in the townlands of Lurga and Tawnyinah, where the hills rise to about 700 feet. The exposures are more or less isolated by drift and bog. The dips are steep and the strike north-east–south-west. In the south-east there is a group of rocks consisting mainly of "felsites", similar to those described by Gardiner and Reynolds (1909, 1910, 1912, and 1914) in the Ordovician west of Lough Mask. They are porphyritic rocks with large corroded quartz crystals, feldspars, and occasional pyroxenes in a felsitic groundmass. There are subsidiary tuffs and agglomerates. In the north-west there is a tuffaceous group, in which the chief rock-type is a coarse, massive green feldspathic tuff. Subsidiary agglomerates, lavas, fine-banded tuffs, and cherty shales are interbedded with the massive tuffs.

The following fossils were found in black cherty shales, in a road-side quarry (loc. A) just over a mile south-south-west of Lurga cross-roads, at the highest point on the road from Lurga to Glentavraun :—

Didymograptus spp. (extensiform) .	Common
Didymograptus cf. *deflexus* Elles and Wood.	Rare.
Isograptus gibberulus (Nicholson) cf. *nanus* Ruedemann.	Rare.


2½m. Charlestown
ONE MILE
Carracastle 1½m
40
TUFF
B
80
65
LURGA
75
74
80
48
Glen School
54
78
A
62
TAWNYINAH
UGGOOL
ORDOVICIAN
TUFFACEOUS GROUP
FELSITE GROUP
QUARTZ PORPHYRY
SILURIAN
GREY SANDSTONE
FINE SANDSTONE
LIMESTONE
PURPLE SANDSTONE
RECENT
DRIFT & BOG

Tetragraptus sp. . . . . 1 specimen.
Glossograptus sp.. . . . . 1 specimen.
Oncograptus sp. . . . . Common.
Phyllograptus ? sp. . . . . 1 specimen.
Lingula sp.
Acrotreta cf. *sagittalis* (Salter).

This fauna definitely indicates an Arenig age. Volcanic rocks west of Lough Mask are of similar age.

Fragmentary, but indeterminable graptolites were also found in soft grey tuff, interbedded with coarse feldspathic tuff, in a roadside exposure (loc. B) north-east of Glen School.

The occurrence of *Oncograptus* is interesting, since this genus has previously been recorded only from the continents bordering the Pacific.

The writer is much indebted to Dr. O. M. B. Bulman for revising the graptolite identifications, and to Dr. J. C. Harper, who introduced him to the area and helped in many ways.

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Contact of Tertiary Lavas with Torridonian near Broadford, Skye

By E. B. Bailey

Abstract

It is argued that the Strollamus outcrop of Tertiary basalt lavas reaching south to Coire Garbh occupies a volcanic inbreak or sink dating from the lava period; and that the Broadford Dolerite is not metamorphic.

Introduction

MANY significant data concerning the contact of Tertiary lavas with Torridonian near Creag Strollamus, north-west of Broadford, are presented by Harker and Wedd in the 1910 edition of the Geological Survey one-inch Sheet 71 with its accompanying memoir. In addition I found a 10½ inches to the mile map by B. C. King (1953) very accurate and useful. During a week at Broadford I had every help from E. H. Francis and I am also grateful to the Carnegie Trust for financial assistance and to the Geological Survey for access to unpublished field-maps.

The pre-Mesozoic structural relations of the Torridonian Sandstone (Pre-Cambrian) and Durness Limestone (Cambro-Ordovician) of the district were described in a recent paper (Bailey, 1954).

Mesozoic Sediments

Judd's contributions to Hebridean Mesozoic geology remain outstanding though made in days of very inadequate topographical maps (1878). Particularly delightful, as emphasizing a close connection with Antrim, was his discovery of remnants of Upper Cretaceous at the base of Tertiary lavas in Mull (1873) and Morvern. Later workers have found further small patches elsewhere in Mull (two localities), Eigg, Skye (three localities), Scalpay, and Raasay, and a tumbled block in the throat of an Arran volcano. Since Judd's days the main workers on Hebridean Mesozoics have been Woodward, Wedd, and Lee. The most serviceable accounts are by Lee and Pringle (1932) and Richey (1935; 1948).

In *Antrim* Trias and Upper Cretaceous emerge marginally from beneath extensive Tertiary basalts, and Jurassic rocks are restricted to local survivals of Lower Lias. At Fair Head, opposite the Mull of Kintyre, Dalradian schists rise to 1,300 feet above sea-level. Though in this exalted position usually stripped of Trias, they still carry Upper Cretaceous beneath a cover of Tertiary lavas. This indicates localized relative upheaval of both post-Trias and post-lava date, without corresponding disturbance in the time-interval between the Chalk

and the basalts. South of Loch Neagh, whatever the reason, Tertiary lavas extend beyond both Upper Cretaceous and Triassic outcrops.

In *Mull* and *Morvern* : (1) Lias is almost continuous between Trias and Upper Cretaceous, and in much of Mull includes Middle and Upper as well as Lower Lias ; (2) Inferior Oolite, with a few feet of Great Estuarines, is preserved S.E. of the Great Glen Fault ; (3) a strip of Kimmeridgian has escaped erosion, apparently through falling into a cleft opened on the Great Glen Fault (Bailey, 1925, p. 114 ; Manson, 1934, p. 83).

In *Ardnamurchan* Trias where present is thin ; and though the Jurassic reaches locally to the base of the Great Estuarine Series Tertiary lavas sometimes extend smoothly on to a platform of Moine schist.

In *Muck*, *Eigg*, *much of Skye*, *Scalpay*, *and Raasay* the Trias-Jurassic succession, capped by remnants of Upper Cretaceous, usually continues well into the Oolites. Our district lies in the heart of this relatively full development, with Trias 0–50 feet, Lias 1,500 feet, Oolites, mainly Inferior Oolite, Great Estuarine Series, and Corallian, over 1,000 feet, and Upper Cretaceous thin (Richey, 1948, p. 21).

Wedd's *Camasunary Fault* (1910, pp. 9, 150) deserves careful attention because it introduces complications into the relations of the Skye Mesozoics and Tertiaries. Near Camasunary House on the shore of Loch Scavaig, 8 miles W.S.W. of Broadford, it has a downthrow to the S.E. that " must exceed 2,000 feet ". It is there demonstrably of post-Corallian pre-Upper Cretaceous date ; and on its upthrow side Tertiary lavas rest either on Lower Lias or Torridonian, with or without intervening Upper Cretaceous. A couple of miles inland the Camasunary Fault is lost to sight under these lavas, which in turn are cut across by a flood of granophyre. It aims, however, at the strait of Caol Mor between Scalpay and Raasay (Text-fig. 1), and in a sense must separate the Strollamus Oolites, including Corallian, from Lower Lias, which at Sligachan is overlain immediately by Tertiary lavas.

Presumably the Camasunary Fault belongs to the same set of movements as were responsible for (1) pre-Upper Cretaceous erosion of Trias at Fair Head ; (2) preservation of the narrow fault-strip of Kimmeridgian in Mull, and (3) development of Kimmeridgian boulder beds at Helmsdale on the north-east coast of Scotland (Bailey and Weir, 1932).

Tertiary Lavas

Basalt lavas of Scalpay and Strollamus are finer in texture, and apparently less basic than many occurring elsewhere in the Hebrides. They have been sufficiently disturbed, pneumatolysed, and contact-

altered to render their bedded succession very obscure. Still Harker and King think that reliable traces of trap-featuring can sometimes be detected ; and I agree. Harker has estimated the thickness preserved in Scalpay as between 1,500 and 1,600 feet (1904, p. 8 ; 1910, p. 137).

In Antrim and the Hebrides in general we have seen that the Tertiary lavas, often with a little intervening Upper Cretaceous, may rest on very different members of the Trias and Jurassic. Even so the divergence of dip between Tertiary lavas and pre-Cretaceous sediments escapes visual recognition. Moreover, only one example is known, and that on a very minor scale, of marked irregularity of contact (Bailey, 1930, fig. 9, p. 109).

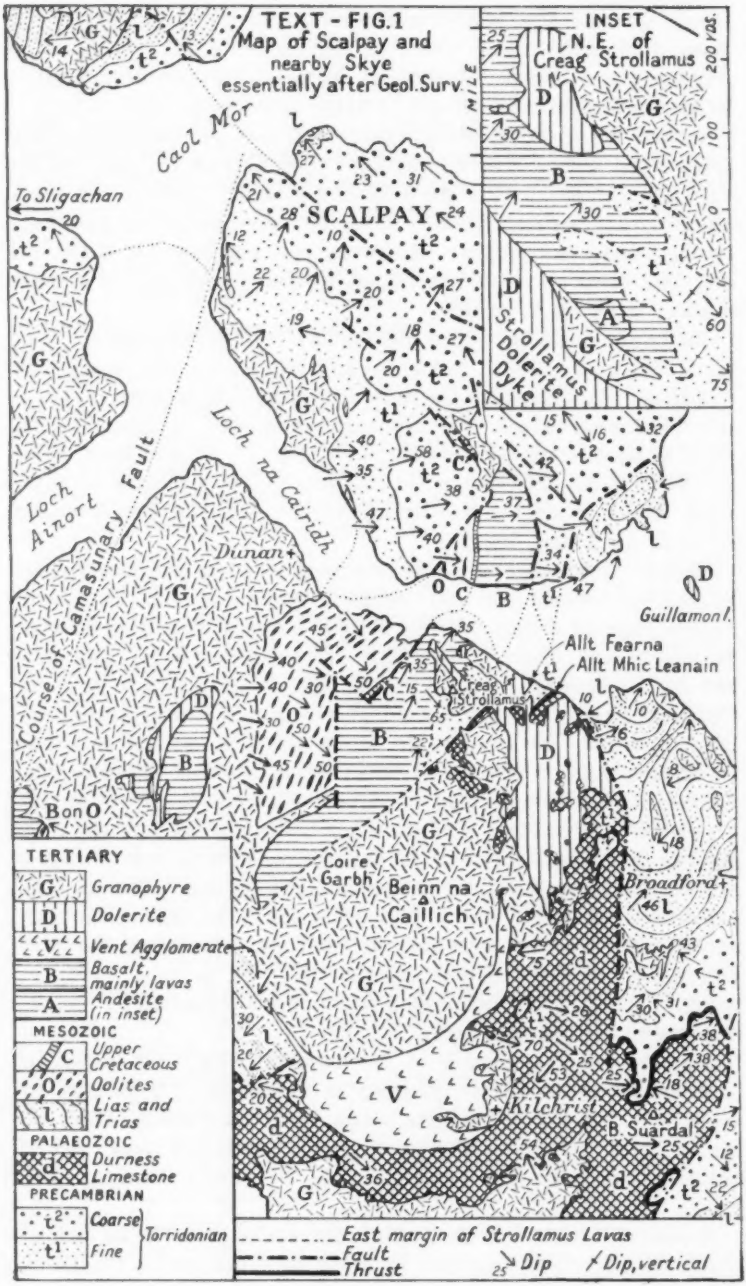
In the few localities where the Tertiary lavas extend beyond their usual Mesozoic pedestal, they apparently retain a smooth base, except in Rhum. Here they actually bank up against a steep slope of Torridonian Sandstone and Tertiary granophyre (see especially Black, 1952, in conjunction with Harker, 1908, figs. 17, 37, and Judd, 1874, p. 254). Judd first recognized this utterly extraordinary arrangement. It is associated with a striking volcanic upheaval, also described by Judd (cf. Bailey, 1945).

Harker realized that the Strollamus-Scalpay district was once covered by Jurassic continuing up into Corallian. At the same time he thought he had detected a strip of country, four miles by three lying between Strollamus and Kilchrist, in which Tertiary basalt lavas habitually rest on Torridonian or on Durness Limestone. He seems to have felt that since Tertiary basalts rest on Torridonian at Loch Scavaig they may reasonably be expected to repeat the performance at Creag Strollamus. Still, he was not satisfied that his hypothetical Strollamus-Kilchrist upheaval antedated the Upper Cretaceous. To quote his own words : " Whether such post-Jurassic but pre-Volcanic elevation belongs to a single epoch or to two distinct epochs, one Mesozoic and the other post-Mesozoic, we are not able to decide " (1904, p. 415).

Harker's uncertainty was in part prompted by an aggomerate neck at Kilchrist. He found that Jurassic rocks are, after basalt, the most important constituent of the agglomerate (1904, p. 18) ; which, of course, implied that the immediate neighbourhood retained its Jurassic cover when volcanicity started.

Scalpay consists essentially of Torridonian. This is (1) capped by Trias in the north-westerly extremity of the island ; (2) intruded by underlying Tertiary granophyre along Loch na Cairidh ; and (3) hidden by downfaulting of Lias along the south-east coast, and of Oolites, Cretaceous and Tertiary, facing Strollamus (Harker, 1904, fig. 2).

It seems probable that the Torridonian received most of its inclination in Tertiary times, because : (1) in the north-east part of the island,


TEXT - FIG. 1
Map of Scalpay and nearby Skye essentially after Geol. Surv.
INSET
N.E. of Creag Strollamus
1 MILE
200 YDS.
Caol Mor
To Sligachan
SCALPAY
Strollamus Dolerite Dyke
Loch Ainort
Camasunary Fault
Loch na Cairidh
Dunan
Guillamon I.
Allt Fearna
Allt Mhic Leanain
Creag Strollamus
Coire Garbh
Beinn na Caillich
Broadford
Kilchrist
B. Suardal
TERTIARY
G Granophyre
D Dolerite
V Vent Agglomerate
B Basalt, mainly lavas
A Andesite (in inset)
MESOZOIC
C Upper Cretaceous
O Oolites
l Lias and Trias
PALAEOZOIC
d Durness Limestone
PRECAMBRIAN
t² Coarse
t¹ Fine
Torridonian
East margin of Strollamus Lavas
Fault
Thrust
Dip
Dip, vertical

its characteristic dip, about 25° N.W., corresponds with that of the associated Trias ; (2) towards the south-west, this dip swings round in relation to the granophyre, and is generally directed N.E. or E. at angles between 20° and 50° ; (3) a similar dip of about 40° E. affects the neighbouring downfaulted Oolites, Cretaceous and Tertiaries ; and (4) a S.E. dip develops where the Torridonian approaches the downfaulted Lias along the S.E. coast, which latter tends to be synclinally disposed.

The outcrop of downfaulted Oolites, Cretaceous and Tertiary (Wedd, 1910, pp. 131–3) pursues an arcuate course, measuring three-quarters of a mile across at the coast, and tapering to nothing 1½ miles inland. The downthrow is great. On the coast the boundary fault to the N.W. cuts out the coarse Torridonian (say, 4,750 feet, Harker, 1910, p. 63), and Lias (say, 1,500 feet) ; while that to the east omits in addition the Oolites (say, 1,000 feet) and basalts (say, 1,500 feet).

The fault on the north-west runs straight N.E. for nearly a mile before turning abruptly N.W. At the bend it brings basalt lava against Torridonian. Its course is then obscured by a transgressive intrusion of felsite, beyond which it serves as south-eastern boundary to a strip of Upper Cretaceous. The companion fault on the east runs north and north-eastwards with a much more smoothly arcuate course. On the *Skye shore* of Loch na Cairidh granophyre passes south-eastwards under Inferior Oolite that is tilted away from it eastwards or south-eastwards at 40°. The top of the granophyre is here at a stratigraphical horizon several thousands of feet higher than in Scalpay. It therefore seems clear that the arcuate fault that bounds the Oolite outcrop in the latter island curves away to the west in its underwater course, and is there transgressed by the granophyre as indicated in Text-fig. 1.

The Skye Inferior Oolite passes eastwards under Great Estuarine Series, and this, for half a mile inland, passes under Corallian capped by Upper Cretaceous (Wedd, 1910, p. 132), thus providing a great sedimentary succession dipping somewhat S. of E. at 40° (Wedd, 1910, fig. 12, p. 119). There can be no doubt that these Skye Oolites with their capping of Upper Cretaceous are in essential continuity with their counterparts across the water in Scalpay ; and these in turn with the basalt lavas which (in Scalpay) follow to the east.

The straight mile-long coast-line running E.S.E. past Creag Strollamus is greatly obscured by faulting (King, 1953, p. 396), and must be left undescribed in this brief account. *Inland the exposures of Tertiary lavas in the Strollamus district* extend a couple of miles south-eastwards, and sometimes measure a mile across. Their western limit against Mesozoics is shown by the Geological Survey as determined by three zig-zag faults, reproduced in Text-fig. 1. West of these faults, as we have seen, the Mesozoic sediments form the roof of the Loch

na Cairidh granophyre, from which they dip S. of E. at about 40°. East of the same, the Tertiary lavas seem to function as roof of the Beinn na Caillich granophyre, and are inclined away from it E. of N. at anything between 10° and 35° ; but their only exposed contact with this granophyre lies along the Coire Garabh " Fault ", which is one of the scenic features of Skye geology, but still awaits detailed description. On the whole it appears probable that the zig-zag faulting which brings the lavas against the Mesozoics on the west was in part coupled with more or less contemporaneous intrusion of the two named granophyres.

The eastern boundary of the Strollamus outcrop of lavas is similar to the western, but more extravagant. For a mile from the shore, until it contacts (perhaps merges with) the concealed continuation of the Coire Garbh " Fault ", it separates the lavas from Torridonian. Dipping E. of N., lava after lava abuts against the latter, so that marginal flows near the coast are presumably much higher in the sequence than their fellows reaching the contact further south. The strike of the Torridonian is at right angles to that of the lavas as shown in the inset of Text-fig. 1.

The transgressive lava-Torridonian junction just described maps with a much more complicated course than can be attributed to ordinary faulting ; so much so that Harker and King have interpreted it as due to unconformity. The irregularity shows both north and south of the Strollamus dolerite dyke—which latter can be recognized in Text-fig. 1 with a broad N.W. outcrop passing close to the summit of Creag Strollamus. To the south, however, the irregularity is little more than is shown by the undoubted faulting of Scalpay. To the north the inset in Text-fig. 1 reproduces King's mapping of the basalt-lava outcrop seen on the steep northern face of Creag Strollamus, except that I have classed as andesite (A) a small area that King mapped as Torridonian—a trifling correction. The basalt and Torridonian outcrops do interdigitate much as shown by King—exact accuracy is not possible. There are two " fingers " of Torridonian projecting into the basaltic area, one of them over 100 yards long. The associated basalt looks like lava, and is sometimes freely vesicular. King thinks he can detect " rapid chilling " as a prevalent feature of contacts (1953, p. 361) ; but after careful examination I remained doubtful of the significance of the observation. The difficulty is that the Torridonian is greatly shattered, and is riddled with intrusions, many of them basaltic. I could never be certain that such intrusive contacts as I saw close to the main basalt margin really belong to the main basalt.

I also found it impossible to distinguish with precision the three-dimensional geometry of the interdigitating junction. Not infrequently basalt rises as a scarp overlooking adjacent Torridonian ;

but this does not settle the question as to whether it occupies an inbreak or neck or belongs to an unconformable cover. King, having no doubt that the relationship is one of unconformity, is certain that " over much of the steep hill slope immediately to the north-east of the summit area the sub-volcanic surface is being re-exposed almost in its original form at the present day " (1953, p. 369). I must confess that the facts which I am in process of assembling in this paper lead me to reject the unconformity hypothesis and to adopt the obvious alternative that the intricate junction of basalt and Torridonian masks the border of a volcanic inbreak.

Hints regarding the early date of this inbreak are afforded by an observation of Harker's that bits of Torridonian can be recognized in lavas and associated conglomerate and ash north-east of Loch Cuil na Creag, 500 yards S.W. of the summit of Creag Strollamus (1904, pp. 13, 27, 40). There is also his record of " several small patches of grit, probably Liassic, involved in the lavas " at Coire Garbh (1904, p. 13). He remarks that the presence of these Mesozoic sediments " is not easily explained " ; I suggest that these have been landslips from the walls of a continuation of the Strollamus volcanic sink, now obscured by granophyre intrusion.

The *Torridonian* bordering the Strollamus lavas differs from the Torridonian adjacent to the Scalpay subsidence in being :—

(1) Very much steeper ;
(2) everywhere shattered (in Scalpay shattering is restricted to close proximity to faults) ;
(3) riddled by intrusions, many of them basalt and themselves greatly broken.

Considered together it seems probable that these peculiarities all belong to the Tertiary volcanic history of the district. Accordingly I suggest that the Torridonian was upheaved alongside the Strollamus sink in much the same abrupt manner as Harker has demonstrated for the Durness Limestone alongside the Kilchrist neck (1904, fig. 4). Hawkes has cited what may be Icelandic analogues (1945, p. 190).

It has been mentioned more than once that the Strollamus Torridonian is riddled with intrusive basalts. Speaking of a locality " extending for 500 yards along the N.W. side of Allt Fearna ", Harker says : " we have a surface of the Torridonian sandstone from which the lavas have been stripped away. With the standstone we see little patches of basalt, the biggest not much over a hundred yards in length. They resemble the lavas which come on in force a short distance away, but they are not outliers of them. They do not lie on the surface of the sandstone, but traverse it and are involved with it in intricate fashion. The larger outcrops are long in comparison with their breadth and have their long axes in the direction of the dykes of the district. They

are too irregular in outline to be termed dykes, but we must regard them . . . as representing the channels by which the lavas rose through the Torridonian Sandstone" (1904, p. 12). Two of the more important irregular intrusions of the locality I found to be just as vesicular as the lavas further west. If their outcrops had happened to be confluent at one extremity or other with the main lava outcrop, they would have given the latter the same sort of irregular outline as is presented north-west of the Strollamus dolerite dyke.

King's reaction to the phenomenon seems to me a little mixed. Let us review it under three headings :—

(1) Speaking of steep slopes north of the Strollamus dolerite dyke (as I call it), he says : "where innumerable small patches of basalt are involved with the Torridonian, the forms are as often irregularly dyke-like as apparent relics of overlying flows" (1953, p. 361).

(2) South-west of the dyke, towards the locality specially singled out by Harker, he notices examples that "appear to have been emplaced by explosive drilling rather than by simple dilation", which "would accord with Harker's conclusion that they represent feeding channels to flows now removed by erosion" (1953, p. 366).

(3) All the same, in part of the area he claims to be able to recognize "numerous small relics" of lava "resting on the Torridonian", to such an extent as to indicate that "the sub-volcanic surface and the present erosion surface are very nearly coincident"—a hypothesis that he has employed in contouring what he takes to be the sub-volcanic surface (1953, p. 370, fig. 2).

The paragraphs numbered (1) and (2) should in themselves be a warning against accepting the conclusion indicated in paragraph (3). Furthermore, even if paragraph (3) stood by itself, it would, I think, stand self-condemned. King *knows* that certain patches of basalt are patches of lava, and *deduces* therefrom that the present surface of erosion incessantly intersects the pre-lava surface of erosion. For my own part, I *know* that this conclusion is too special to be true, and therefore *deduce* that the patches belong to intrusions irregularly penetrating the Torridonian through and through. I learnt this forty years ago when I published a note suggesting that numerous small patches of breccia in Mull might be relics of an unconformable cover (1912). Further research, especially by C. T. Clough, E. M. Anderson, and G. V. Wilson, demonstrated the alternative view that the breccia occupied necks, which could be ground down, but not brushed away (1924, p. 199).

On the *Durness Limestone* outcrops beyond the Strollamus Torridonian, both Harker and King have interpreted a few small scraps of associated basalt as lavas. The only description of such a patch is given by King (1953, pp. 361–2). He notes (1) that "flinty textured

rock forms two thin horizons " within what he calls lavas, (2) that against the limestone " irregular contacts with small apophyses " are common " as might be expected in view of the present-day configuration of the surface of limestone outcrops ", and (3) that " the dips are around 30 degrees to the south-east . . . in marked contrast to the usual trends ". In the field I found the supposed " lavas " to be really a group of three or four thin parallel intrusive sheets, each with chilled top and bottom.

Harker did not make the mistake of recognizing " lava " at the above locality ; but his own examples are quite unconvincing. One (1904, fig. 28, p. 131) shows basalt peering through peat and moraine without anything whatever to suggest that it is a lava. Another lies within a quarter of a mile of the great Kilchrist agglomerate neck, which Harker himself has noted to be full of downfallen Mesozoic debris.

Broadford Dolerite

By Broadford Dolerite I mean the complex that Harker and King have called Broadford Gabbro. Mostly it is dolerite, though merging patchily into gabbro, and also, especially towards its margins, into basalt.

Part of the complex is the Strollamus dolerite dyke, which extends for a mile N.W. of Allt Fearna and measures about 100 yards across. This dyke frequently develops basaltic edges. Harker, strangely enough, in two incidental references says that on Creag Strollamus the Broadford Gabbro " takes the form of a sheet " (1904, pp. 99, 451). I cannot understand this allusion, if it means anything more than that the dolerite here frees itself of the extremely irregular habit characteristic of it further east. Still less can I understand King's interpretation of the Strollamus dolerite dyke as metamorphosed lava preserved in a narrow graben (1953, fig. 4, p. 374).

I do not know the detailed relations of the Strollamus dyke to the main mass of the Broadford Dolerite. The latter " is intruded chiefly ", Harker says, into the Durness Limestone ; " but this statement does not adequately express what is seen on the ground, for [in most of the area concerned] the limestone is seen only in the form of small detached portions in the igneous rock. There are fifty of these enclosed patches, varying in dimensions from 300 to 20 yards, besides others down to 10 feet or less in diameter, which are too small to be mapped. In ground-plan they always present convex outlines to the gabbro, and the smallest ones are circular " (1904, p. 97).

I agree with Harker that the wide distribution of these patches shows that they must occur throughout much of the dolerite, for they are seen where present-day erosion must be sampling very different levels of the intrusion. At the same time I think he is wrong in supposing

that each limestone outcrop is the cross-section of a pillar (" columnar portion ", 1904, p. 99). He is, however, undoubtedly correct in regarding the geometrical behaviour of the dolerite as repeated in that of neighbouring granophyres where these happen to be intruded into Durness Limestone. This leads him convincingly, I think, to attribute the special type of geometrical association to something in the nature of limestone as contrasted with non-calcareous country-rock.

Harker felt that : " Where gabbro now appears on the map was once limestone, and this limestone has vanished as completely as if it had been annihilated. It can only have been removed either in blocks or fragments or in solution in the gabbro magma, and neither of these hypotheses, nor a combination of them, is easily applied. . . . Even if the chief bulk of the limestone can have been carried away in fragments, as suggested, the smooth rounded form of the junctions compels us apparently to admit a certain amount of solvent action," and yet the composition of the gabbro does " not afford any support to the supposition " that it has dissolved an appreciable amount of the limestone. So that " we are compelled to leave the question unsolved " (1904, p. 99).

For myself I should prefer to attribute any solution of the limestone that may have occurred to the action of subterranean acid waters, which before or during the arrival of magma upon the scene may have redeposited much of the limestone at the surface as travertine. This, however, I regard as mere speculation. It is important to realize that the admixture of country-rock and intrusion here developed is no more intimate than that characteristic of cone-sheet complexes in Mull ; though the pattern, of course, is quite different.

What seems tolerably certain to me is that much of the Broadford dolerite is emplaced as a very irregular penetrative sheet in the Durness Limestone. To the north-east, in my opinion, dolerite and limestone are faulted down together under the Broadford spread of Lias. The dolerite probably reappears in this direction in Guillamon Island.

King adopts a different explanation. Undeterred by their multiplicity, he attributes all the limestone exposures in the dolerite outcrop to small crags over which basalt lava (now metamorphosed to dolerite) poured in past ages. " It is concluded that the gabbro has everywhere been emplaced immediately above the sub-volcanic surface " (1953, p. 375, and fig. 2). Curiously he does not note that on this hypothesis the dolerite and limestone must part company when they reach the fault mentioned above. The dolerite, if it is really metamorphosed Tertiary basalt lavas, must be faulted *up* over the Broadford spread of Lias, whereas the associated Durness Limestone must contrarywise be faulted *down* under the same. This is not an impossible conception, but it is definitely difficult.

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Tear Faults in the Barnesmore area, Donegal

By G. P. Leedal and G. P. L. Walker

Abstract

Tear faults cutting the Barnesmore Granite in County Donegal are described. The Lough Belshade fault trends N.E.–S.W., and there has been a lateral movement along it in a left-handed or sinistral sense of 2·2 miles; it is believed to be of the same age as the Great Glen Fault. The Barnes Lough Fault crosses and displaces the Lough Belshade fracture, and may be, in part at least, Tertiary. Although the movement along it is much smaller, it has taken place in the opposite sense.

THE Caledonian granite intrusion of Barnesmore forms 20 square miles of rugged and uninhabited country in County Donegal in the north-west of Ireland. A number of faults traverse the granite and shift the outcrop of its margin, and it is the purpose of this paper to describe the faulting, which is interesting in that it appears to include tear faulting of two different ages.

The district in which the Barnesmore Granite Complex lies was mapped in 1881–5 by E. W. Egan, J. R. Kilroe, and W. F. Mitchell of the Geological Survey of Ireland, and a map (sheet 24) on the scale of 1 in. to the mile was published in 1888, accompanied by an explanatory Memoir. The faults were mapped, and the Lough Belshade Fault was described as having "a downthrow to the south . . . accompanied by a very extensive horizontal displacement". We remapped the area in the summers of 1949 and 1950, and obtained new data on the nature and age of the numerous faults cutting the granite mass.

The most noteworthy fracture is the Lough Belshade fault, astride which is the beautiful but little-known corrie-lake from which the fault is named. The fault trends N.E.–S.W. and cuts transversely across the granite mass. Its course is marked by a prominent erosional feature; the Owendoo River is guided for several miles by it, the Lough Belshade corrie has developed on it, and a prominent fault-line scarp has been formed where the granite margin has been shifted and high granite ground now overlooks the lower schist country on the other side of the fault.

The fault plane is vertical, and can be seen in the cols N.E. and S.W. of Lough Belshade, where it is exposed over a vertical distance of several hundred feet. It is accompanied by a belt of intense crushing up to a hundred yards wide which is veined by quartz, calcite, haematite, and pyrite. Slickenside striations have been observed at several points; just over a mile S.W. of Lough Belshade they are inclined 10° S.W., while in the col on the other side of the Lough they are inclined rather more steeply in the opposite direction.

The Lough Belshade fault has displaced the outcrops of both margins of the granite a distance of about 2·2 miles in a left-handed or sinistral sense. The granite margin is everywhere inclined outwards at a moderate or large angle, and there is no doubt that the fracture is a tear fault along which there has been lateral movement of about 2·2 miles. Certain features of the internal structure of the granite point to a vertical displacement of the order of 2,000 feet with downthrow on the S.E. side, in addition to the lateral displacement ; and where the fault enters the Carboniferous area on Banagher Hill limestone on the S.E. is downfaulted against the thick basal conglomerates of the Carboniferous on the N.W.

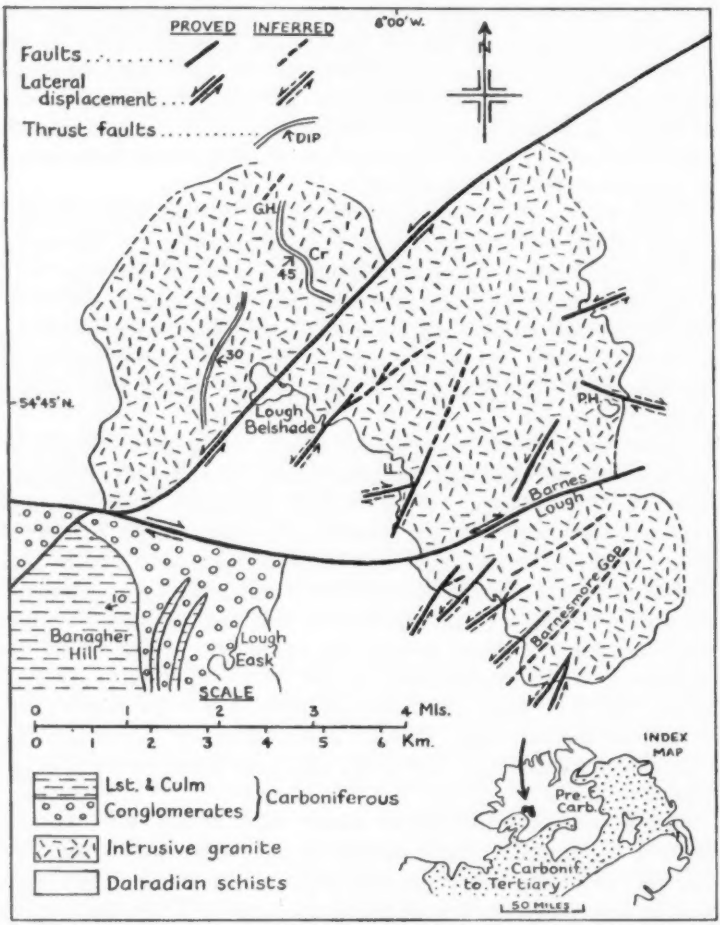
North-west of the granite mass the Lough Belshade fault has been shown on the one-inch Survey maps (sheets 19 and 24, Geological Survey of Ireland) to displace the outcrop of a bed of quartzite in the Dalradian about 2 miles in a sinistral sense. At the western end of the granite the fault is bent and offset by another fault before resuming its south-westerly course and passing into the Carboniferous of Banagher Hill. In all the fault is traceable with certainty for at least 15 miles.

The second prominent fracture traversing the Barnesmore granite is that which passes through, and gives rise to, the deep valley of Barnes River and Barnes Lough. This fracture trends E.N.E.–W.S.W. and displaces the margins of the granite in a right-handed or dextral sense. That the Barnes Lough fault is a second tear fault is fairly clear from the evidence of the displacement of the granite margins, although the eastern margin is partly obscured by drift and bog, and of certain internal contacts between granite and aplogranite sheets within the mass itself. The horizontal shift on this fault is, however, only 0·15 miles. Where it is exposed traversing the granite at the western end of the Barnes River valley, the fault is vertical and is accompanied by a good deal of crushing of the rocks, which are veined by amethystine quartz.

Traced westwards the Barnes Lough fault swings W.N.W. and becomes the boundary fault separating the Carboniferous rocks of Banagher Hill from the schists and granite to the north. Here there must be a considerable downthrow to the south, but that the fracture is still a tear fault is indicated by the bending and off-setting of the Lough Belshade fault.

The Barnesmore granite mass is traversed by a large number of " lanes ", or shallow, steep-sided, rectilinear valleys. Most of these represent lines of crush, but in twelve only has faulting been proved. It is rather surprising that the Barnesmore Gap, which is so prominent a topographic feature, is not a large fault. Fracturing of the granite there certainly is, but no displacement of the granite margins can be

demonstrated, although the exposures are not sufficiently good to preclude the possibility that some movement has taken place. A belt of very intense crushing, almost comparable to that found along the Lough Belshade fault occurs in a small stream which descends to the



Geological sketch-map showing the faults cutting the Barnesmore Granite Complex. (G.H. = Glascarns Hill ; Cr = Cronloughan ; P.H. = Pollakeeran Hill ; I.L. = Illanmore Lough.)

Owengarve River north of Glascarns Hill. Unfortunately exposures of the granite contact are here masked by a considerable thickness of drift and bog, and faulting cannot be demonstrated.

Most of the proved faults trend approximately N.E.–S.W., and shift the outcrops of the granite margin left-handedly; on one dislocation

an internal contact between granite and aplogranite has been shifted in the same sense. Though it is not possible to state definitely that any of these are tear faults, the manner in which they displace the granite margins suggests that they are left-handed tear faults of the same set as the Lough Belshade fault. Two faults, one north of Pollakeeran Hill and the other south of Illanmore Lough, trend N. 75° W. and N. 75° E. respectively, and displace the granite margin in a dextral sense. Again definite proof of the movement is lacking, but they are probably right-handed tear faults similar to the Barnes Lough fault.

A fault of a different kind is exposed in the vicinity of Cronloughan; it is not vertical like the others but dips at about 50° towards the north-east. This is beautifully illustrated by the manner in which its outcrop crosses the two ridges walling the Cronloughan corrie. The fault is very well exposed in gullies descending from both sides of the northern ridge, and also south of Cronloughan. Locally it is followed by dykes of the Caledonian and Tertiary swarms. It is believed that this fracture is a reversed fault displacing aplogranite sheets several hundred feet. A second, similar, fracture west of Lough Belshade is also followed in part by a Caledonian dyke and it, too, may be a reversed fault, although no conclusive evidence of movement has been found.

The Barnesmore granite was intruded into Dalradian schists after their folding and regional metamorphism, and it is cut by a swarm of dykes of Caledonian type, fragments of which are found in the basal conglomerates of the Carboniferous on Banagher Hill. The granite is thus of Caledonian age, one of the Newer granites of the British Caledonides. The faults which cut the Barnesmore granite are later than local deuteric alteration of the granite, but many of them had been initiated before the injection of the Caledonian dyke swarm, although some of these dykes were later sheared.

It is known that movement along the Lough Belshade fault continued after Lower Carboniferous times, although at present we have no way of deducing what proportion of the movement was post-Lower Carboniferous. Several Tertiary dolerite dykes enter the fault zone without themselves being crushed, which places an upper limit to the age of the fault, and in the col N.E. of Lough Belshade a 3-ft. Tertiary dyke crosses the fault without being offset or broken. It seems probable that the fault is of the same age as the well-marked set of left-handed tear faults with N.E. trend in the Scottish Highlands, of which the Great Glen fault is the best example. W. Q. Kennedy (1946) regards the greater part of the movement along that fault as having been accomplished in pre-Upper Carboniferous times.

The Barnes Lough fault cuts the Lower Carboniferous on Banagher Hill and is at least in part post-Lower Carboniferous. Near the

western end of the Barnes Lough valley several N.W.-trending Tertiary dolerite dykes, on approaching the fault, change direction and follow it for a short distance, before resuming their N.W. course on the other side. Two of these dykes are seen crossing crushed granite in the fault zone but are not themselves crushed. However, one mile west of the western extremity of the granite and a short distance north of the fault are two dykes of quartz-dolerite that are crushed and heavily altered. Though it cannot be certain that these dykes are Tertiary, they are nevertheless of Tertiary type, and are quite unlike the Caledonian dykes in the area. Although they might possibly be Carboniferous or Permo-Carboniferous, they are much more likely to be Tertiary and indicate that some movement along the Barnes Lough fault took place after the intrusion of the Tertiary dyke swarm. The fact that the Lough Belshade fault is itself displaced proves that most of the movement along that fault was accomplished before the initiation of the Barnes Lough fault. According to current conceptions of the dynamics of faulting (Anderson, 1942), the Lough Belshade and Barnes Lough faults could not have been produced by the same stress conditions, and it is suggested that the latter fracture is very much later than the Lough Belshade fault, and is of late- or post-Carboniferous or possibly Tertiary age.

We wish to express our thanks to Dr. G. Wilson for valuable suggestions and for reading the MS. of this paper.

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A Study of Calcite Twinning in the Strathavon Marble, Banffshire

By R. H. Clark

Abstract

It is possible, from study of twinned calcite grains in a thin section of marble, to locate the most probable positions of the applied stresses likely to have caused the twinning. By this means inferences may be drawn as to the stress system operative during the late stage deformation of the marble.

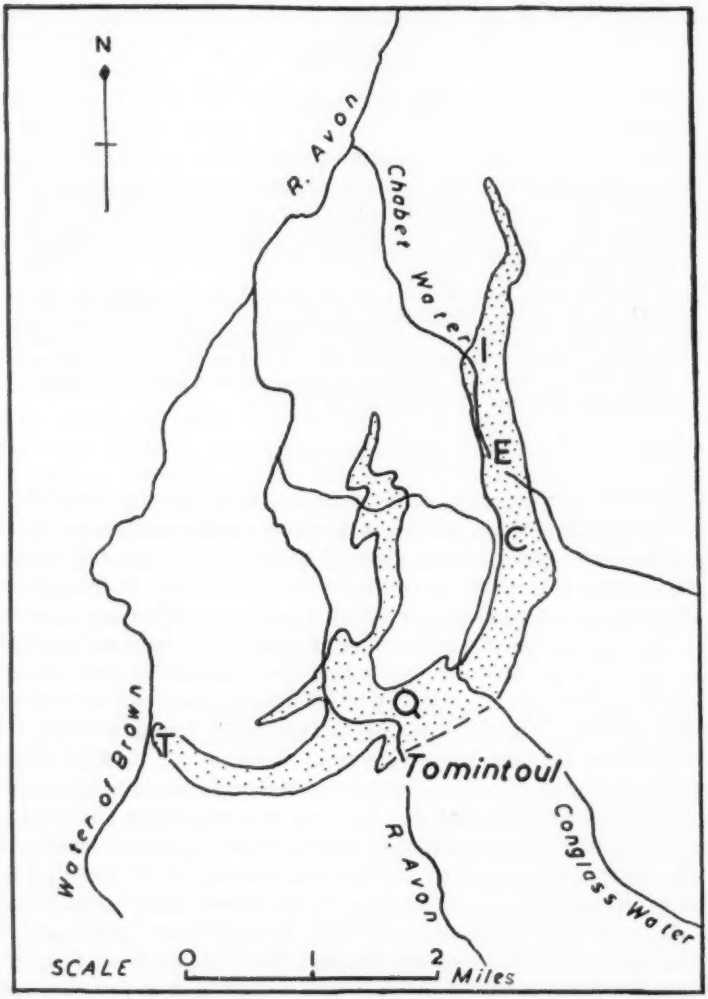
Marble outcrops over an area of about 5 square miles, in the Tomintoul region of the Scottish Highlands, have been investigated. It has been found that a consistent stress pattern exists for the area as a whole. The calcite twinning can best be explained by a N.E.–S.W. compression applied normal to the trend of the regional fold axis, followed by a mild N.–S. squeeze.

Introduction

In many marbles some grains of calcite show twinning on $\{01\bar{1}2\}$. Knowledge of the behaviour of calcite compressed or elongated experimentally under known physical conditions (Griggs and Miller, 1951), makes it possible to construct the orientations of the applied compression and tension axes which would most effectively account for the observed pattern of twinning in a naturally deformed marble. Turner (1953, p. 297) has shown that the compression and tension axes deduced for calcite grains can be remarkably consistent throughout a thin section. Further work by McIntyre and Turner (1953) on a marble from the Grantown–Tomintoul region of the Scottish Highlands has demonstrated that this homogeneity can extend to specimens collected a foot apart, and that the axes of compression and tension deduced to account for twinning in three marbles, from localities several miles apart, approximate to a great circle normal to the mean direction of the regional axis of folding. In the course of an investigation of the Loch Tay limestone, near Loch Fyne, Gilmour and Carman (1954) discovered that over the hundred feet of outcrop studied, the deduced stress system was constant with respect both to foliation and to geographic direction.

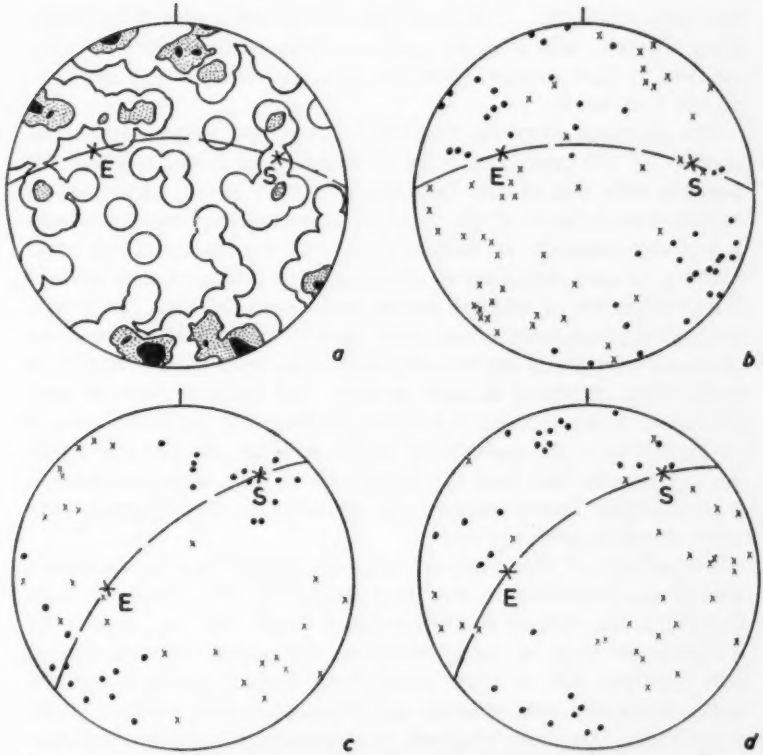
The present study was undertaken by the writer, at the suggestion of Dr. McIntyre, to test the degree of homogeneity of the inferred stress system responsible for the twinning of calcite in the Dalradian marble of Strathavon, over a large portion of its outcrop.

The tectonic setting of the Strathavon region has been described by McIntyre (1951). The marble is folded with graphite-schists in the form of a major recumbent fold, the axis of which (= the *b* axis of the fabric) plunges towards the south-east at nearly 30°. The present



TEXT-FIG. 1.—Locality Map. Strathavon marble shown dotted. C = Croughly; E = Ellick; I = Inverchor; Q = Tomintoul Quarry; T = Tombreac.

writer has verified the orientation of the fold axis by his own observations in the field; the trend and plunge is remarkably consistent over the whole area. The form of the marble outcrop is complex (Text-fig. 1), but in a general way it extends for a distance of about 8 miles in a N.E.–S.W. direction, and has a maximum thickness (near Tomintoul) of the order of 1,500 feet. Good exposures are few, and normally



TEXT-FIG. 2.—Lower hemisphere projections of Tomintoul and Ellick marbles. Plane of projection in all cases normal to regional fold axis. Foliation is right and left; at the top is the normal to foliation upwards. The horizontal plane through south and east is shown.

(*a*) Marble from roadside quarry near Tomintoul. 100 [0001] axes in calcite. Contours 1–3–5 per cent per 1 per cent area.

(*b*) Same locality as (*a*) above. Compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for twinning on observed twinned $\{01\bar{1}2\}$ lamellae.

(*c*) Marble from small quarry 200 yards west of Ellick Farm, Glen Chabet. Compression (dots) and tension (crosses) which would give maximum resolved shear stress favourable for twinning on observed twinned $\{01\bar{1}2\}$ lamellae of twenty-five well-twinned grains.

(*d*) Marble specimen collected from a point 15 feet above (*c*).

consist of small farm quarries, where the material was formerly worked for lime; a notable exception is the large road-metal quarry at the roadside near Tomintoul.

PROCEDURE FOLLOWED

Specimens were collected from six different outcrops of the marble. One of these was taken from the roadside quarry near Tomintoul,

two from the largest of the small quarries (situated near Ellick Farm, Glen Chabet), and a single specimen from each of the four farm quarries in Glen Chabet, Glen Conglass, and Glen Brown (T, C, E, and I, Text-fig. 1).

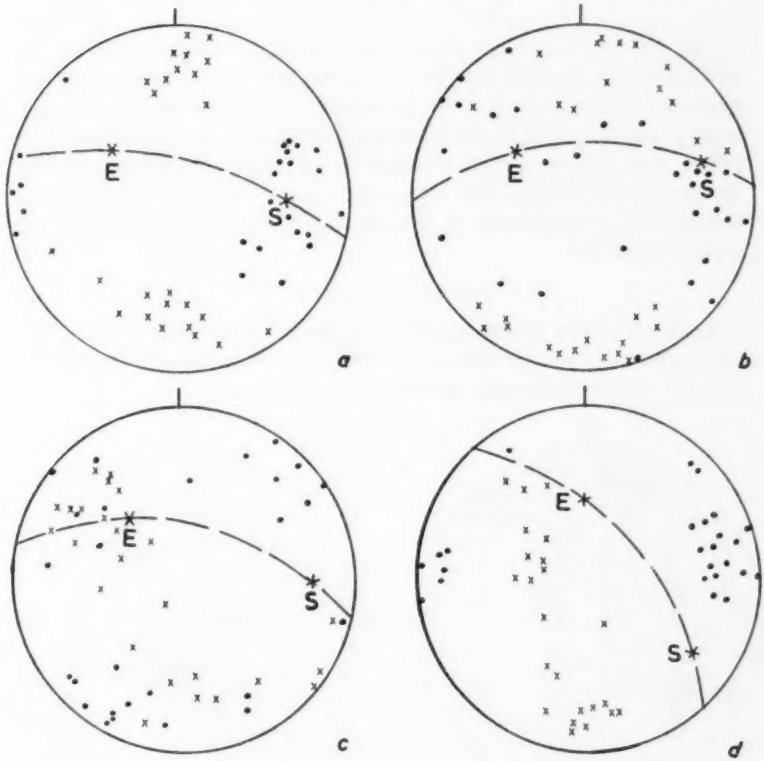
The specimen from the Tomintoul quarry was subjected to a full analysis of 100 grains, in order to compare its fabric as closely as possible with that of the specimen from this locality described by McIntyre and Turner (1953, p. 227). However, for present purposes it was not necessary to analyse completely the fabrics of the other marbles, as only directions of compression and tension axes deduced from orientation of twinned calcite grains were required. Only relatively strongly twinned grains were used for determining these directions and such grains can be easily selected by inspection. Twenty-five grains were measured in each section. All sections were cut perpendicular to *b*; as there is a strong tendency for the [0001] axes to lie normal to *b*, the majority of $\{01\bar{1}2\}$ lamellae, the poles of which are distant only $26\frac{1}{4}°$ from the [0001] axes of their respective crystals, were therefore ideally situated for scanning on the universal stage under moderate angles of tilt.

The validity of this method is clearly demonstrated by consideration of the Tomintoul marble, and also of the two specimens from Dulnain Bridge studied by McIntyre and Turner (loc. cit., pp. 232–5). Although in each of these specimens 100 grains were measured, only relatively few of these would have sufficed to determine the compression and tension axes, and these and other suitable grains could easily have been obtained by inspection of a section cut perpendicular to *b*. The technique of measurement of a limited number of twinned grains has also been used successfully by Gilmour and Carman (1954, p. 55). In all these marbles the identification of the original lattice as contrasted with the twinned lattice was considered to be unambiguous.

The Tomintoul Exposure

A specimen from the roadside quarry near Tomintoul was collected from a point about 50 feet distant from McIntyre and Turner's specimen (1953, pp. 227–232, and Text-figs. 2–3).

The orientation diagram (Text-fig. 2*a*) for [0001] axes in 100 grains encountered in three parallel traverses of one section shows that the fabric of the specimen closely resembles that of the marble studied by McIntyre and Turner (1953, Text-fig. 2*a*). The [0001] axes have a preferred orientation, in a girdle about *b*. The girdle is not quite so strongly developed as that found by McIntyre and Turner, but the strong maximum recorded by these writers close to *c* is again conspicuous. The compression and tension axes obtained from the more



TEXT-FIG. 3.—Lower hemisphere projections of various marbles. Plane of projection is normal to regional fold-axis. Foliation is right and left, and the top is the normal to foliation upwards. The horizontal plane through south and east is shown. The dots are compression, and the crosses tension which would give maximum resolved shear stress favourable for twinning on observed twinned {01$\bar{1}$2} lamellae of twenty-five well-twinned grains.

(*a*) Marble from Tombreac, Glen Brown.

(*b*) Marble collected quarter of a mile south of Croughly, Glen Conglass.

(*c*) Marble collected quarter of a mile west of Inverchor, Glen Chabet.

(*d*) Marble from locality quarter of a mile south of Ellick, Glen Chabet.

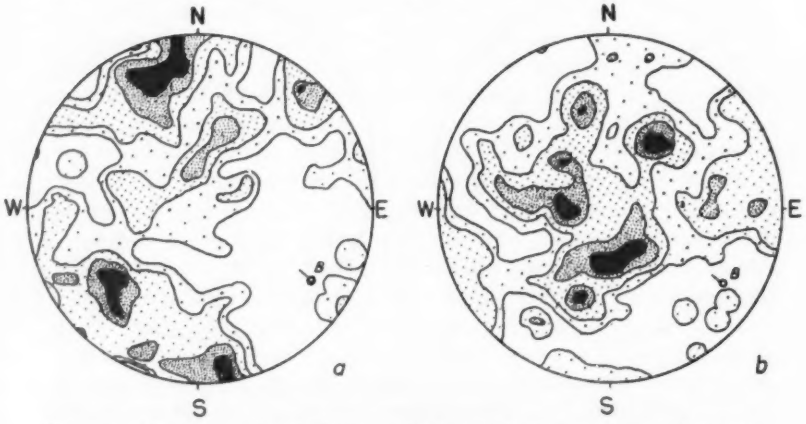
strongly twinned crystals (Text-fig. 2*b*) show reasonably marked concentrations, and these correspond very closely with those obtained by McIntyre and Turner (1953, Text-fig. 2*c*). These similarities suggest that the whole fabric is essentially homogeneous within the field of the quarry.

Ellick, Glen Chabet

The quarry near Ellick Farm, Glen Chabet, is the largest of the smaller exposures of the marble. Two specimens, separated by a vertical interval of about 15 feet, were examined. In both cases a reasonably strong concentration of compression and tension axes was found to exist; and the respective orientations of these correspond closely in the two specimens (Text-fig. 2*c* and *d*). This agreement tends to confirm the homogeneity of the stress system within the field of a quarry exposure.

Other Localities

Analyses of the single specimens collected from each of the four additional localities are shown in Text-fig. 3. In each case concentrations of compression and tension points are evident.



Text-fig. 4.—Lower hemisphere projections of compression and tension axes from all six localities examined. One specimen only used from each locality. Plane of projection horizontal. *B* marks the position of the regional fold axis.

(*a*) Compression axes. Contours 0·5–1–2·5–3·5 per cent per 1 per cent area.

(*b*) Tension axes. Contours 0·5–1–2·5–3·5 per cent per 1 per cent area.

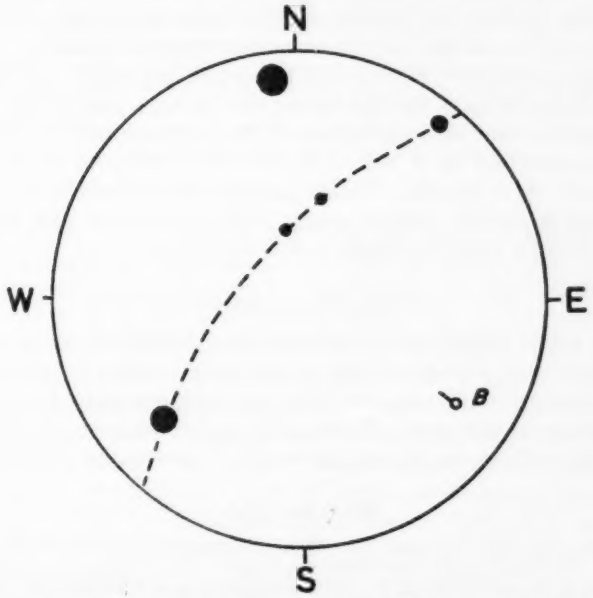
Conclusions

The following conclusions are based on comparative study of all the compression-tension diagrams.

(*a*) At each locality the compression and tension points show preferred orientations, in general forming distinct maxima 90° apart.

(*b*) The maxima formed by the compression axes are generally rather more marked than those of the tensions: in two specimens

(Text-fig. 3*c* and *d*) the tension maxima are elongated into diffuse girdles normal to the respective compression maxima. This is especially noteworthy, for in a marble with a concentration of [0001] axes in twinned grains, such concentration must be reflected in the tension axes rather than in those of compression (the tension axes are only 19° from their respective [0001] axes; compression axes are 71°). The concentration of compression axes and the relative spread of tension axes occurring in the Strathavon marbles strongly favours



TEXT-FIG. 5.—Diagrammatic representation of the more important compression maxima of Text-fig. 4 (*a*). The maxima are indicated by dots, of sizes proportional to their relative magnitudes. Four of the dots lie in a girdle which corresponds almost exactly to the *AC* plane normal to the regional *B* axis.

compression as the dominant factor in the late stage deformation of the area.

(*c*) The compression and tension maxima for all specimens tend to lie in a girdle about the fold-axis, although the positions of the maxima with respect both to foliation and to geographic orientation are not identical in all localities. However, when the compression and tension diagrams for each locality are rotated into the geographic horizontal plane (Text-fig. 4*a* and *b*), a consistent pattern for the region as a whole becomes apparent. The compression axes are arranged in a broad

diffuse girdle, nearly normal to the mean direction of the regional fold axis (Text-fig. 4*a*). On close examination this girdle is seen to consist of two components (Text-fig. 5):—

(i) A sharply defined narrow girdle almost exactly normal to the regional fold axis. This girdle contains two nearly horizontal N.E.–S.W. maxima.

(ii) A fairly broad horizontal N.–S. maximum about 35° from the narrow girdle.

The tension axes (Text-fig. 4*b*) form a group of maxima not far from the vertical, their precise locations apparently being controlled by the positions of the maxima of the compression diagrams.

These dispositions suggest that the forces responsible for the late stage deformation of the Strathavon marble were almost horizontal. In fact, the observed twinning in all the marble specimens can best be accounted for by a N.E.–S.W. horizontal compression followed by a final N.–S. squeeze. The late squeeze, though sufficient to cause twinning in suitably oriented calcite grains, was not of such intensity as to produce macroscopically visible structures.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to Dr. D. B. McIntyre, who introduced him to the study of marble fabric; and to Professor F. J. Turner, for valuable assistance and advice in the preparation of this paper. Some of the equipment used was obtained with a grant from the Moray Endowment, University of Edinburgh.

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The Occurrence of Orthoclase and Microcline in the Granitic Gneisses of the Carn Chuinneag-Inchbae Complex, E. Ross-shire

By R. I. Harker

Abstract

Optical examination of the potash feldspars in the granitic gneisses of the Carn Chuinneag-Inchbae complex suggests that both orthoclase and microcline occur together—not infrequently in the same crystal. Optic axial and extinction angles, intermediate in value between those characteristic of the two polymorphs, have been recorded and plotted graphically. X-ray powder diffraction patterns confirm that both orthoclase and microcline are present together in these rocks. It is believed that most of the microcline developed from orthoclase during the regional metamorphism of the area, which permitted recrystallization at a lower temperature than that at which the orthoclase was formed.

Introduction

MANY of the " Older Granites " of the Scottish Highlands are presumably para-tectonic, i.e. their formation is associated with the regional metamorphism of the Moine and Dalradian series. On the other hand, the acid orthogneisses of the Carn Chuinneag–Inchbae complex are representatives of those granitic rocks which were emplaced during a pre-tectonic phase. The granitic gneisses in this area are surrounded by Moine schists and " granulites " in which hornfelses have survived as the relics of an original aureole (*Geol. Survey Mem.*, 1912 ; Tilley, 1935). The pelitic schists of the region as a whole characteristically consist of biotite, muscovite, quartz, and oligoclase, whilst the widespread occurrence of almandine, but not kyanite (or staurolite), is an indication of the grade of regional metamorphism attained.

The acid orthogneisses can be subdivided into a number of different varieties but the majority are composed essentially of quartz, potash feldspar, acid plagioclase, and biotite. The " Inchbae rock ", which is a coarse-grained augen gneiss, is typical over a large area of the complex. Its chemical composition is given in Table I where a comparison can be made with the average of ninety biotite granites (Johannsen, 1932, p. 228).

This paper is concerned with the potash feldspar of the granitic gneisses.

Optical Description

The heterogeneous character of the potash feldspar is very noticeable in many microscope sections when viewed with polarized light, and especially in specimens of the less foliated granitic gneisses. It appears that both orthoclase and microcline are present. Carlsbad

twinning may occur in the former and cross-hatch twinning is common in the latter. There can also be found single grains whose optical properties vary in different parts of the crystal, between those characteristic of orthoclase and those characteristic of microcline. In the memoir (*Geol. Survey Mem.* 1912) explaining the Scottish Geological Survey's " one-inch " sheet No. 93, the potash feldspar of the " Inchbae rock " is described by Flett as follows : " The microcline structure . . . is frequently local, appearing in part of a felspar phenocryst but fading away in other portions " (loc. cit., p. 89). As the rocks become more deformed the amount of microcline appears to increase at the expense

TABLE 1

	I. *Wt.%*	*II.* *Wt.%*
SiO_2	74·59	71·55
Al_2O_3	12·29	14·47
TiO_2	0·31	0·11
Fe_2O_3	0·95	1·46
FeO	2·25	1·10
MnO	0·03	0·05
MgO	0·25	0·87
CaO	1·47	1·97
Na_2O	2·67	3·04
K_2O	4·50	4·12
H_2O+	0·34	0·78
H_2O-	0·08	—
P_2O_5	0·12	0·32
	99·85	99·84

I.—" Inchbae rock," 3,000 yards W.S.W. of Inchbae Lodge (analyst, R. I. Harker).
II.—Biotite granites. Average of ninety analyses (Johannsen, 1932, p. 228).

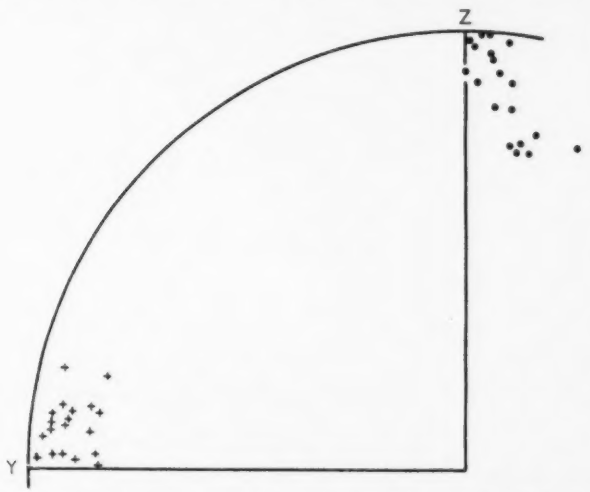
of the orthoclase, and in the most foliated rocks the potash feldspar is all microcline. The large augen, frequently of microcline-perthite, break down as deformation increases, to mosaics of microcline which, as it appears under the microscope, is never perthitic.

Microcline most frequently makes its initial appearance as a rather patchy development of the typical cross-hatch twinning at the rim of a crystal round which the twinning may completely or, more often, partially extend. The coarseness of the twinning is very variable, often being extremely fine and imparting a shadowy extinction to the crystal. Where microcline is developing from orthoclase the orientation of the two with respect to each other is always as nearly the same as the structures allow. Thus in a crystal partly of orthoclase and partly of microcline the cleavages and partings cut right across the crystal, whilst the optic planes are very approximately parallel.

A study of some of these potash feldspars was made on the universal stage to determine the variations in optic axial angle and in the orienta-

tion of the optical indicatrix. An accuracy of $\pm 2°$ is claimed for the values of 2V given and only crystals in which it was possible to measure the angle directly were utilized. The plotting of the (001) and (010) cleavages could be checked only so far as the angle between the two is, within the limits of accuracy of the universal stage, always 90°. It was found that the accurate determination of positions of extinction was greatly facilitated by using the large crystals and a low magnification.

Text-fig. 1 shows how the positions of z^* and y^* (i.e. the perpendiculars to (001) and (010) respectively) vary with respect to the optical

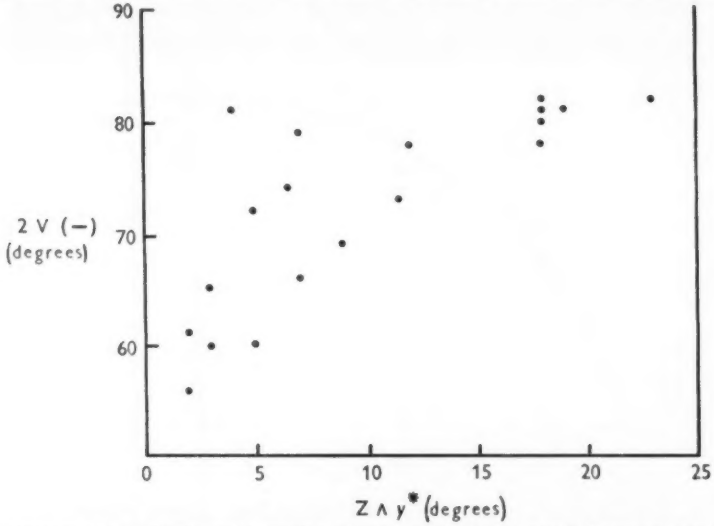


TEXT-FIG. 1.—Stereographic plot to show how the positions of y^* and z^* vary with respect to X, Y, and Z, the axes of the optical indicatrix, in the Orthoclase–Microcline series.

directions X, Y, and Z. It will be seen that whereas there is a considerable scatter of points representing z^*, those representing y^* show a more definite trend from orthoclase through intermediate types to microcline. In Text-fig. 2, 2V has been plotted against the angle $Z \wedge y^*$ for the same feldspars as in Text-fig. 1.

The association of orthoclase and microcline appears to be characteristic of other pre-tectonic "Older Granites" of the Highlands. For example, orthoclase and microcline are reported in the augen gneisses (derived from biotite granites) of Windyhills and Portsoy (*Geol. Survey Mem.*, 1923). At Ben Vuroch, too, there is evidence that the potash feldspar of the granitic gneisses is not all of one kind, for maximum extinction angles on to the (010) cleavage observed in sections in the [010] zone vary from 0 to 18°. A 2V as low as 60° was recorded

in a crystal which had straight extinction on to (010) in the [010] zone. The association of orthoclase and microcline has been described in different rocks from other metamorphic areas. It has been reported recently in the granulites of Lapland (Eskola, 1952, p. 148), and in the schistose sparagmites in the Rondane area (Oftedahl, 1950, p. 203). Dolar-Mantuani (1952) made measurements with the universal stage on potash feldspars in the Westkettle rocks, and plotted on a stereogram the positions of y^* and other crystallographic directions, with



TEXT-FIG. 2.—Optic axial angles plotted against the angle between the Z axis of the optical indicatrix and the perpendicular to (010) for some potash feldspars in the acid gneisses of the Carn Chuinneag-Inchbae complex.

respect to X, Y, and Z. She found an appreciable variation in optic axial angle and in the orientation of the indicatrix but concluded on p. 526 (loc. cit.): "The present data indicate that only microcline occurs as potash feldspar in the Westkettle rocks . . . Some deviations which are established from the normal values of 2V and of co-ordinates of the crystallographic elements of microcline are believed to be due to inexact determinations . . ."

In the course of making the measurements on the Carn Chuinneag-Inchbae potash feldspars, it was clear that some of those which were optically triclinic were apparently untwinned. A. F. Wilson (1950) made similar observations on the potash feldspars of some Australian charnockitic rocks. Dolar-Mantuani (1952, p. 517), describing the microcline of the Westkettle rocks, pointed out "that areas where twinning disappears completely may be optically monoclinic or

triclinic ". Just as microcline may not show cross-hatch twinning, such twinning may be shown by a potash feldspar even when the departure from monoclinic symmetry is only very small.

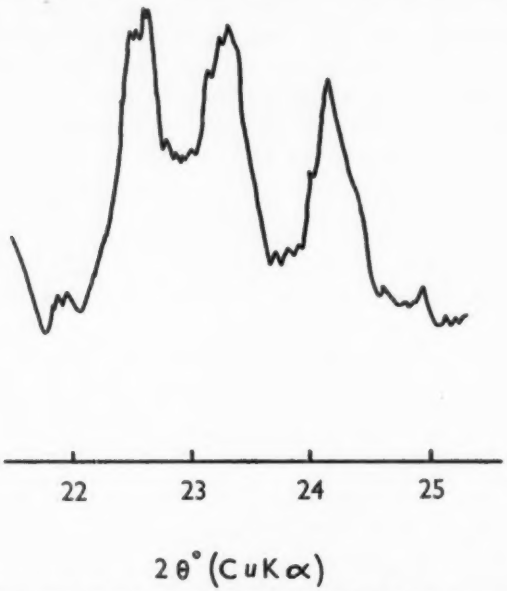
X-ray Analysis

In the potash feldspar from the Carn Chuinneag-Inchbae complex it has been observed that optically at least there are all gradations between orthoclase and microline, but the question arises as to whether structurally this is really the case. It has been shown by Laves that low temperature monoclinic potash feldspars do exist but he has also shown that some potash feldspars may be optically monoclinic or show a variable deviation from the monoclinic only by virtue of the sub-microscopic twinning of a microcline lattice (Mallard's hypothesis). This he found to be so in a microcline from Madagascar (Laves, 1950, p. 553). He also gives reason to believe that monoclinic optics are sometimes produced by the submicroscopic twinning of lattices structurally intermediate between orthoclase and microcline (see also Laves, 1952, p. 443).

In order to determine whether in fact a structurally monoclinic potash feldspar is present in the Carn Chuinneag-Inchbae acid gneisses, an analysis was carried out on the X-ray spectrometer. For this particular study the large potash feldspars from a fine-grained apparently porphyritic granitic gneiss were utilized. In thin section these potash feldspars could be seen to have a variable development of cross-hatch twinning and a shadowy extinction. Text-fig. 3 shows the relative intensities of the (130) and ($1\bar{3}0$) reflections.[1] The two outer peaks are produced by the microcline structure in which the (130) spacing is different from the ($1\bar{3}0$) spacing whilst the single peak in the centre is produced by the (130) and ($1\bar{3}0$) planes of the monoclinic orthoclase structure. [The significance of the position and separation of the (130) and ($1\bar{3}0$) peaks in low temperature alkali feldspars has been described by Mackenzie (1952).] It appears that the amount of intermediate material in this sample is much less than that of either orthoclase or microcline, indicating that the transition from one to the other is effected across a relatively narrow zone.

[1] It must be pointed out that before that part of the powder diffraction pattern shown in Text-fig. 3 could be regarded as significant, it was first necessary to ascertain that the amount of impurity in the sample in the form of albitic plagioclase is not appreciable. This is because the albite pattern includes a peak, though not a very strong one, coincident with that corresponding to {130} of orthoclase which could thus be obscured by it. In the present case, the X-ray spectrometer was run through a sufficient range of 2θ (20° to 70°) to show, by observation of the strong albite reflections, that the amount of albitic plagioclase included as perthitic and/or sub-microscopic inclusions is only very small. It could not account for that peak seen at $2\theta = 23{\cdot}5°$ (CuKα) which must therefore be equivalent to {130} of orthoclase.

It would seem, therefore, that the monoclinic mineral orthoclase really is present in the acid orthogneisses of the Carn Chuinneag-Inchbae complex. This does not deny that there may also occur here potash feldspar which appears to be monoclinic, or approaching monoclinic symmetry, only by virtue of submicroscopic twinning. Indeed this might partly account for the greater variation in optic



TEXT-FIG. 3.—Part of the powder diffraction chart for a sample of potash feldspar from a granitic gneiss in the Carn Chuinneag–Inchbae complex. The three major peaks represent X-ray reflections from the (130) and (1$\bar{3}$0) planes.

axial angle as the potash feldspars approach optical monoclinic symmetry, see Text-fig. 2. At the moment, however, little is known about the effect of submicroscopic twinning on optic axial angles.

CONCLUSIONS

With regard to the potash feldspars in general; it would appear that care is required before a given example can be accurately described as orthoclase or microcline especially when the potash feldspar in question occurs in metamorphosed rocks. The absence of the characteristic cross-hatch twinning does not preclude microcline, neither does the presence of cross-hatch twinning indicate the degree of departure from monoclinic symmetry. A straight extinction on to (010) in all sections of the [010] zone can only indicate that the potash

feldspar is not an untwinned variety of microcline. The optic axial angle may well be more diagnostically useful, for although the exact effect of composition, e.g. the albite content, is not known, it is probably only slight (Tuttle, 1952).

With regard to the potash feldspar of the Carn Chuinneag-Inchbae complex there is little doubt that at least some of it was originally orthoclase in the unmetamorphosed granitic rocks and that on recrystallization, effected by the later regional metamorphism, a large proportion of it has inverted to microcline. It appears that as the rocks become more deformed, recrystallization was facilitated and the perthites were able to clear themselves into two well separated phases, so that the orthoclase and microcline perthites have eventually become replaced by non-perthitic microcline in the most foliated gneisses. Similar annealing processes as this have been described in the rocks of other regions, e.g. Phemister (*Geol. Survey Mem.*, 1926), Buddington (1939), and Chayes (1952). There is as yet, however, no definite indication that the transition from orthoclase to microcline must be accompanied by a compositional change and the orthoclase in a given composite crystal may appear just as perthitic as the microcline which is derived from it. Whether shearing stress has promoted the development of microcline in any way other than by causing intergranular movement and facilitating recrystallization at a lower temperature is still a matter for speculation and the possible effects of high hydrostatic pressure should not be completely ignored. However, it is considered that this orthoclase to microcline transition provides further field evidence of the instability of orthoclase proper below a certain temperature at the lower end of the geological temperature scale. Other lines of supporting evidence are, for example, the comparative rarity of orthoclase in pegmatites and of truly authigenic orthoclase in unmetamorphosed sediments In several cases where the latter has been reported, e.g. Daly (1917), Goldich (1934), and Berg (1952), the term has probably been used in a general sense to include adularia and no optical or X-ray data are given.

Acknowledgments

The writer is indebted to Drs. O. F. Tuttle and W. S. Mackenzie, through whose kindness and encouragement the X-ray spectrometer analysis was carried out, and to Dr. S. O. Agrell through whom specimens of the Ben Vuroch granitic gneiss were made available.

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The Form of the Eastern End of the Insch Igneous Mass, Aberdeenshire

By M. S. SADASHIVAIAH

ABSTRACT

Peridotite, troctolite, and olivine-gabbro are exposed in the Bourtie area at the eastern end of the Insch igneous mass. The distribution of outcrops suggests that the rocks are disposed in bands running north and south and a smaller-scale north-south banding can be seen in some exposures. The earlier view that the ultrabasic rocks form an east-west lens on the floor of a northerly-dipping gabbro sheet is therefore abandoned and both the northern and southern contacts are believed to be part of the roof of the igneous body.

INTRODUCTION

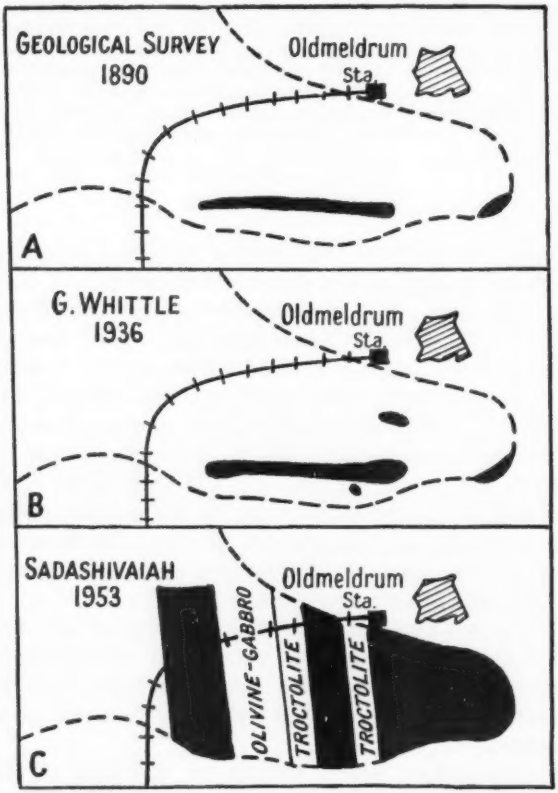
THE shape of the great Insch gabbro body is a subject of some interest and importance in the general geology of North-East Scotland. This mass, which is overwhelmingly gabbroic, is the largest of the intrusions making the Newer Basic province of Aberdeenshire, as can be seen from the maps of Read (1923A, fig. 1). It is elongated in an east and west direction and, as will be indicated below, it has been assumed to form a thick sheet with the roof on the northern and the floor on the southern contact. The writer, together with Professor H. H. Read, has recently completed a field study of the whole Insch Mass and has formed the opinion that all the natural contacts both on the north and the south are parts of the roof. The 80 square miles of gabbro actually seen at the present level of exposure are therefore probably part of a much larger sheet.

Some of the new evidence concerning the shape of the Insch Mass has been derived from a study of the form of the ultrabasic rocks at the eastern end of the mass in the parish of Bourtie, and is described in this present note. Other relevant features of the mass will be dealt with elsewhere.

Earlier investigations with a bearing on the shape of the Insch Mass are few. The southern half of the mass, including the area now to be described, falls within Sheet 76 of the one-inch Geological Survey Map of Scotland; this map was published in 1890 and a short explanation (Central Aberdeenshire), written by L. W. Hinxman and J. S. G. Wilson, appeared in the same year. The peridotites of Bourtie were grouped with other serpentines associated with the Insch gabbros and all were thought to have been produced from the basic rocks by selective metamorphism. On the map, the Bourtie serpentine (peridotite) was shown as a narrow band running east and west in the gabbros, parallel to the southern contact of the Insch

Mass, and a small detached portion almost on the same line appeared at the extreme south-eastern end of the mass (see Text-fig. 1A, in which peridotite is marked in black).

The northern half of the Insch Mass lies within Sheet 86 of the one-inch Survey Map. The geology of this area was described by Read (1923B) who concluded that " the form in space of the whole Insch



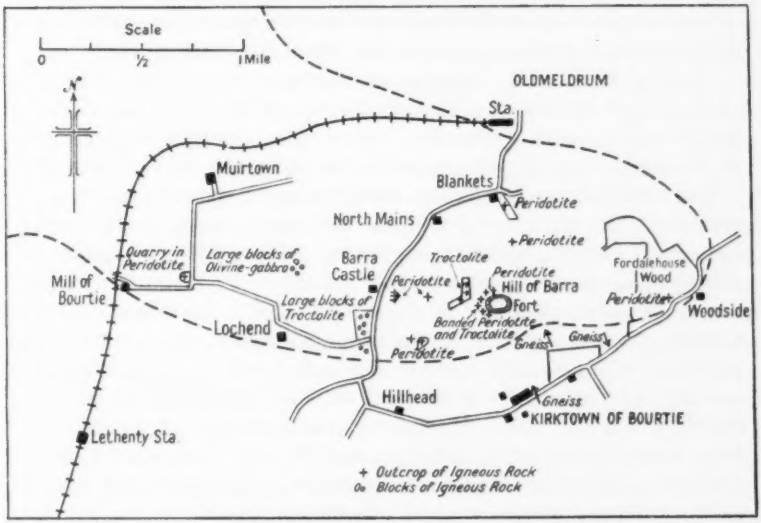
TEXT-FIG. 1.—Interpretations of the form of the Bourtie peridotite (black).

Mass cannot yet be suggested, but we are probably dealing, in Sheet 86, with a sheet-like mass whose top slopes gently northwards " (Read, 1923B, p. 117)—this conclusion being largely based on the very great width of the contact-aureole on the northern margin of the body.

In 1936 G. Whittle studied the eastern part of the Insch Mass and gave the first description of the peridotites and troctolites of the Bourtie area. He tentatively suggested, from the contrast between the poorly-developed thermal aureole on the southern margin of the

mass and the magnificent aureole to the north, that the southern contact was the floor of the intrusive sheet. He regarded the ultrabasic masses as lenticular accumulations of ferromagnesian constituents on the floor of the igneous body (1936, p. 72). Whittle (1936, fig. 7) agreed in general with the Survey outlines for the Bourtie peridotite, but added a couple of masses, one at Blankets and a second south-west of Barra Hill (Text-fig. 1B).

The form suggested by the present writer for the peridotites of Bourtie is quite different from that favoured by previous writers, as can be seen from Text-fig. 1C, where the peridotite is shown as two bodies



TEXT-FIG. 2.—Outcrops of Igneous Rocks in the Bourtie Area.

running north and south. This suggestion is based upon a consideration of all the outcrops in the Bourtie area, and of the banding in some of the exposures. The scarcity of outcrops makes it necessary to describe the evidence in detail.

THE PERIDOTITE, TROCTOLITE, AND GABBRO OF BOURTIE

The outcrops of igneous rocks in the Bourtie area are shown in Text-fig. 2. The country-rocks of this area are siliceous granulites, quartz-biotite-schists, and oligoclase-biotite-gneisses of the Ellon Series (Read, 1952). So far as the exposures permit a generalization the foliation and banding of the Ellon Series are parallel to the main contacts of the igneous body, the regional strike running east and west.

The largest and most continuous outcrop of igneous rock is seen on Barra Hill where, within the ramparts of the old fort and immediately below them on the north-western and south-western slopes, crags of peridotite with scarce troctolitic streaks and bands appear. The lower slopes of the hill are littered with large loose blocks of banded peridotite and troctolite. Banding in these blocks is often beautifully clear but this, unfortunately, is not so in rocks that are definitely in place. By scaling off the weathered edges of outcrops over a considerable area, one obtains an impression of a crude banding running north and south and steeply inclined. Nothing more than an impression can be claimed and certainly nothing so clear and definite as the attitude of troctolite-peridotite banding observed in the Belhelvie Mass (Stewart, 1946) and the Huntly Mass (Shackleton, 1948).

West of Barra Hill, troctolite and gabbro occur in the chevron-shaped coppice due west of Barra Hill Fort and here a definite observation of north and south banding can be made. Peridotite is seen west of the coppice and is well exposed in an old quarry further west still.

The distribution of peridotite, troctolite, and gabbro on the traverse westward from the summit of Barra Hill accords most readily with a large-scale banding trending north and south. Other outcrops off this traverse agree with such an interpretation. Peridotite is found in the small wood south-east of Barra Castle, at a point south of the western peridotite portion of the traverse. Again, due north of the peridotite of Barra Hill summit, the same rock is exposed, almost certainly in place, halfway between the fort and Blankets; Whittle (1936, p. 71) has recorded peridotite still further north in the burn immediately south-east of Blankets farm-house. Due east of Barra Hill, rotten peridotite is exposed in a small old quarry on the south edge of Fordalehouse Wood, west of Woodside.

In the rough ground on the west side of the road, south of Barra Castle, there are many large blocks of well-banded troctolite-peridotite that may not be far off place; no admixture with blocks of other material can be observed here. In the flat ground to the west of Barra Castle, there is a group of large gabbro boulders weathering spheroidally; if these are in place, which is unlikely but not impossible, the proposal of north-south banding is strengthened, especially as peridotite is again exposed in the large old quarry at the road fork east of Mill of Bourtie.

Petrography

The ultrabasic rocks of the Bourtie area include both dunites and peridotites. They are greenish-black rocks speckled with a few whitish areas. In slice, the dunites are seen to be composed almost entirely of partly serpentinized straight-edged olivine crystals, usually closely

packed together but in places separated by angular areas of dense bastitic material derived from a pyroxene. Occasionally, large independent euhedra of an orthopyroxene of Bushveld type (Hess and Phillips 1938) are found between the olivine crystals; such orthopyroxenes show fine lamellae of clinopyroxene and enclose small rounded grains of olivine that serpentinize in a rather different fashion from the main olivine of the rock. A poorly-developed double corona at the margins of some olivine grains indicates that plagioclase originally filled certain of the interstices between the olivines.

By the increase of pyroxene and feldspar in streaks and bands the dunites pass into troctolitic peridotites and gabbros. The white specks increase in size and number to coalesce into irregular bands. The rocks in hand specimen look like troctolites, although sections show that they have the simple troctolitic composition only in narrow bands. In slice, the main components in order of abundance are plagioclase, pyroxene, and olivine. The plagioclase is a labradorite, An_{63}, in tabular crystals showing varying degrees of alteration. By far the most important pyroxene is an orthorhombic variety forming large euhedra, often clustered and usually showing delicate striping with clinopyroxene. Large ophitic plates of clinopyroxene are patchily distributed in some rocks. Olivine forms large irregular serpentinized grains, blackened with iron oxide and in some cases streaked out by movement. Very beautiful double coronas of the type described by Read (1923B, pp. 106, 107, fig. 7) from gabbros of the Huntly Mass and by Stewart (1946, p. 472) from Belhelvie are developed around the olivines at the contacts with feldspar; the narrow inner rim is usually of orthopyroxene and the broader outer rim of fibrous amphibole, often symplectitic. A deep-brown amphibole and a deep-coloured biotite are very minor constituents of the troctolitic rocks and fibrous amphiboles and sericitic material, probably the result of end-stage action, are often present.

One of the bands of basic rock in the chevron-shaped coppice west of Barra Hill fort lacks the troctolitic appearance of the rocks described above, and the section shows that it is poorer in olivine and richer in orthopyroxene; the latter mineral is as abundant as the plagioclase and is often enclosed as separate euhedra in large plates of clinopyroxene. The loose blocks of gabbro mentioned as occurring west of Barra Hill Castle are found in slice to be basic olivine-gabbros very much affected by end-stage processes, so that parts of them have been converted to masses of pale slender amphibole blades.

Discussion

The outcrops and general character of the rocks in the Bourtie area have now been described. These rocks are very much richer in

ferromagnesian components than the gabbros which make up the bulk of the Insch igneous mass, but there can be no doubt that they are a part of the same body. They can be matched with rocks in the other gabbroic bodies of the province.

The mineral banding which can be seen in some of the outcrops and boulders around Barra Hill appears to resemble the much better-developed structure in, for example, the Belhelvie Mass (Stewart, 1946), where it has been regarded as the product of gravitative settling of crystals at the base of a magma chamber. The presence of this structure therefore lends support to Whittle's (1936) suggestion that the rocks of the Bourtie area were formed by the accumulation of early-formed crystals.

It has already been mentioned that Whittle followed the Geological Survey interpretation of the Bourtie peridotite as an elongated mass running *east and west*; he therefore concluded that the southern margin of the igneous body was the floor. The distribution of outcrops which has been described above, however, seems to the present writer to justify the proposition that the peridotite, with troctolite and gabbro bands, forms two bodies trending roughly *north and south*. The suggestion of north-south banding in the troctolite-peridotite and the fact that in the field no kind of east-west feature is made by the peridotite outcrops, strengthen this proposition.

If the form of the Bourtie rocks suggested here and shown in Text-fig. 1C is correct, then the southern contact cannot be the floor on which the ultrabasic rocks accumulated, since they lie almost at right angles to it. The actual contact is not exposed, but the occurrence of hornfelses in the Pitcaple and Oyne districts, further to the west along the southern margin, suggests that it is a natural one. Viewed from any high ground to the west, Barra Hill is seen to be flanked on the south by higher hills of gneiss; the igneous rocks could better go under these gneisses than over them. The writer therefore concludes that the rocks of the Bourtie area, which lie at the eastern end of the Insch Mass, are flanked both on the south and the north by rocks forming part of the roof of the igneous body, and that although they probably lie nearer the bottom and termination of the mass than any of the gabbros to the west, the floor is nowhere exposed.

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The Status of Sillimanite as an Index of Metamorphic Grade in the Kenya Basement System[1]

By L. D. Sanders

(PLATES I and II)

Abstract

Regional studies using certain minerals as indices of metamorphic grade indicate a coincidence between areas of granitic injection or migmatitization and the distribution of sillimanite. Occurrences of that mineral in knotted bodies or *faserkiesel* and in pegmatites and aplites within migmatites have, however, sometimes been attributed to late metasomatism rather than to metamorphic conditions. In view of the doubtful value of the mineral as an index of metamorphic grade in these circumstances its distribution in the Kenya Basement System is reviewed and the field relationships between sillimanite-bearing metamorphosed pelitic sediments and *faserkiesel* migmatites occurring in central Kenya are described.

It is concluded that sillimanite in the migmatites is derived from partly assimilated sillimanite gneisses, which are of extensive but inconspicuous distribution in the non-migmatitized Basement System. The regional stability of sillimanite rather than kyanite over a great area suggests that high-grade metamorphic conditions prevalent in Kenya during Basement System times were accompanied by granitization processes culminating in the local formation of replacive granites in which sillimanite relics are preserved.

Introduction

STUDIES of metamorphic variation made during the past sixty years in areas of regional or thermal metamorphism have often employed specific minerals as grade indices and the conclusions reached have done much to substantiate the usefulness of this method, which was first effectively employed by Barrow (1893), in demonstrating the zonal distribution of sillimanite-, kyanite-, and staurolite-bearing rocks about the granites of the Aberdeen–Angus border. Later investigations, particularly those in the Scottish Highlands and the eastern United States, emphasize the intimate connection between areas of regional granitic injection or migmatitization and the occurrence of sillimanite. Attention has been drawn to the close coincidence between the position of the sillimanite isograd and the limits of the central regional injection complex of Sutherland and the Grampian Highlands by Read (1931) and Kennedy (1949, p. 52). The widespread incidence of sillimanite both as a constituent of *faserkiesel* and in pegmatite and aplite veins within the Scottish migmatites has,

[1] Published by permission of the Commissioner of Mines and Geology, Nairobi, Kenya.

however, caused some doubt that sillimanite found in such environments is directly connected with conditions of regional metamorphism. Watson (1948, p. 149) has advanced the view that the mineral in one area was formed under the influence of pegmatitic solutions and metasomatic activity at a late stage in the history of the migmatitization of the Moine schists, rather than as a high grade end-member of a metamorphic series.

Along the Taconic axis of the eastern United States, sillimanite is found both in high-grade schists and in neighbouring acid intrusions, but opinions concerning the relationship between the two vary. The sillimanite isograd plotted in New York State (Barth, 1936) and its northward continuation in Vermont and New Hampshire, lies close to the western margin of a belt of augen gneisses and intrusions in which sillimanite occurs. In this area the Littleton formation contains horizons of sillimanite schist which appear to conform with a sedimentary sequence rather than to bear a relationship to the granodiorites and monzonites of the "New Hampshire Magma Series" which invade them. Fowler-Billings (1949, p. 1262) records quartz-dioritic intrusions which have engulfed the sillimanite schists, but still contain relics of them in various stages of assimilation. Moore (1949, p. 1642) also attributes sillimanite in the Kinsman quartz monzonite to the digestion of sillimanite schist inclusions. In Pennsylvania, Weiss (1949, pp. 1703–4) considered it impossible to relate the distribution of sillimanite over a broad zone in the Wissahickon schist to the presence of granodioritic intrusions, but Wyckoff (1952, p. 48), working in the same area, came to the conclusion that the mineral was more abundant in or near areas of granitization, and a similar opinion was held by Smith (1945, p. 303) with respect to sillimanite schists of the Piedmont of South Carolina and Georgia.

Sillimanite-bearing migmatites and granites are not uncommon in other areas of regional metamorphism, and the origin of the sillimanite has aroused further speculation. Adams and Barlow (1910) held the view that differentiation of an aluminous fraction from a granitic magma was responsible for sillimanite occurring in granites of the Haliburton–Bancroft area of Canada, whilst Bugge (1945) considered sillimanite knots in a Norwegian gneissose granite to be armoured relics which had been formed in pelitic schist before granitization. Shackleton (1946, p. 9) inclined to the view that *faserkiesel* noted in the Nanyuki-Maralal area of Kenya represent relics in granitoid migmatite.

In view of the conflict of opinion on the origin of sillimanite in areas of regional migmatitization and granitization it may be of interest to summarize some features of sillimanite migmatites occurring in Central Kenya.

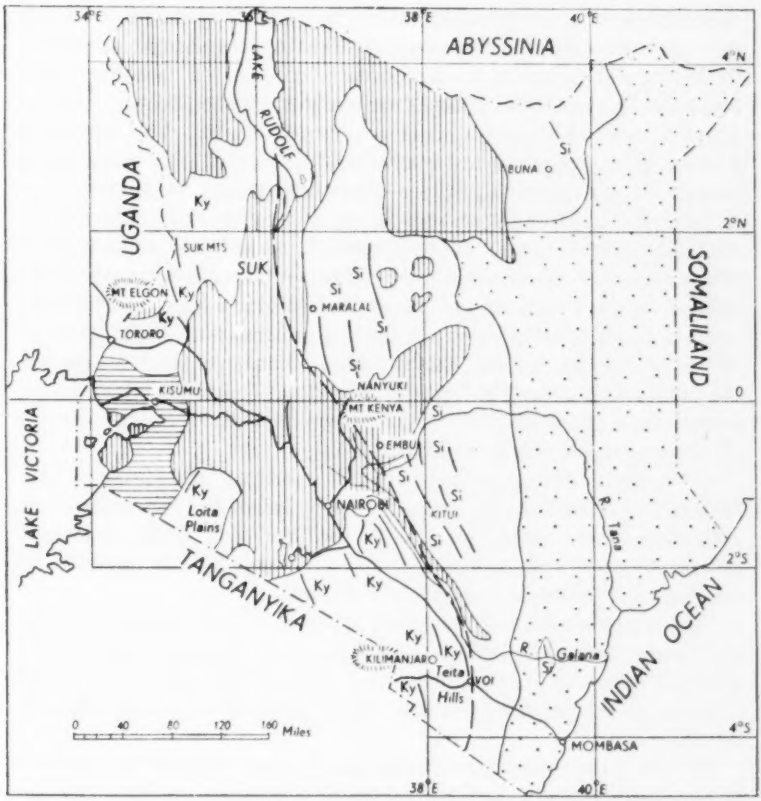
Distribution and Mode of Occurrence of Sillimanite and Kyanite in Kenya

The term Basement System is applied to metamorphic and crystalline rocks which in Kenya Colony have an approximate north–south regional strike and form the northern continuation of the " Mozambiquian orogenic belt " of Portuguese East Africa and Tanganyika. They include numerous horizons of metamorphosed pelitic sediments to which Barrow's zoning by index minerals (chlorite, biotite, garnet, kyanite, and sillimanite) can be applied, but knowledge of the distribution of these sensitive bands is at present inadequate to enable any firm metamorphic zoning to be established. The high-grade indices sillimanite and kyanite are, however, extensively developed where the sediments are sufficiently aluminous, and an indication of the broad distribution of the two minerals is emerging. Kyanite has been recorded mainly in South-Central Kenya, between the Loita plains and the Teita hills. The northward continuation of this section of the Basement System is obscured by Tertiary lavas in Central Kenya, but kyanite gneisses again appear in the Suk mountains in the north-west of the Colony and probably represent a continuation of the zone. Sillimanite on the other hand, is found in the eastern and northern parts of the territory, where it has been recorded in the Northern Frontier Province near Buna, also north and east of Mount Kenya and in a zone extending southwards from Embu through Kitui District to the Galana River (see Text-fig. 1). In an intermediate belt both sillimanite and kyanite sometimes occur together, either in the same rock or in neighbouring horizons.

Both the minerals considered display common features in their mode of occurrence. They are found most frequently in thin but persistent gneisses interstratified with biotite and garnet gneisses and schists. Quartz, feldspar, biotite, muscovite, garnet, and rutile are common associates of both kyanite and sillimanite, which themselves appear generally as minor constituents, although some sillimanite gneisses of Kitui District contain over 35 per cent sillimanite, and the richest kyanite gneisses of Southern Kenya contain over 50 per cent kyanite. Both minerals are also found in quartz veins and pegmatitic segregations, and as lenticular bodies in quartzose rocks.

Sillimanite in Areas of Granitization in Kenya

The intense regional metamorphism to which the Kenya Basement System has been subjected was apparently accompanied by the formation of coarsely crystalline granitoid gneisses. Granitic bodies of batholithic dimensions have not been demonstrated, but considerable sections of the metamorphosed pelitic and semi-pelitic rocks have



TEXT-FIG. 1.—Sketch-map showing the relative distribution of sillimanite and kyanite in the Kenya Basement System.

been converted by alkali metasomatism to microcline-bearing granulites and gneisses which show flowage folding and *boudinage* structures, indicating movement in a semi-plastic condition. It is among such rocks that the granitoid gneisses are likely to be dappled with quartz-fibrolite knots which project from weathered surfaces. The sillimanite is remarkably persistent and sometimes forms small silky patches and streaks in granulites which are otherwise entirely composed of a granoblastic assemblage of microcline, albite-oligoclase, and quartz, with subsidiary biotite or titanomagnetite. Migmatites showing these features are well displayed in the Nuu hills of Eastern Kitui where the gneisses of the Basement System are thrown into a series of folds, the cores of which contain *quartz sillimanitisé* or *faserkiesel*, while horizons of comparatively weakly migmatitized sillimanite gneisses occupy the intervening limbs (see Text-fig. 2). The sillimanite gneisses can be traced into areas of localized granitization where the following sequence of changes appears to have taken place:—

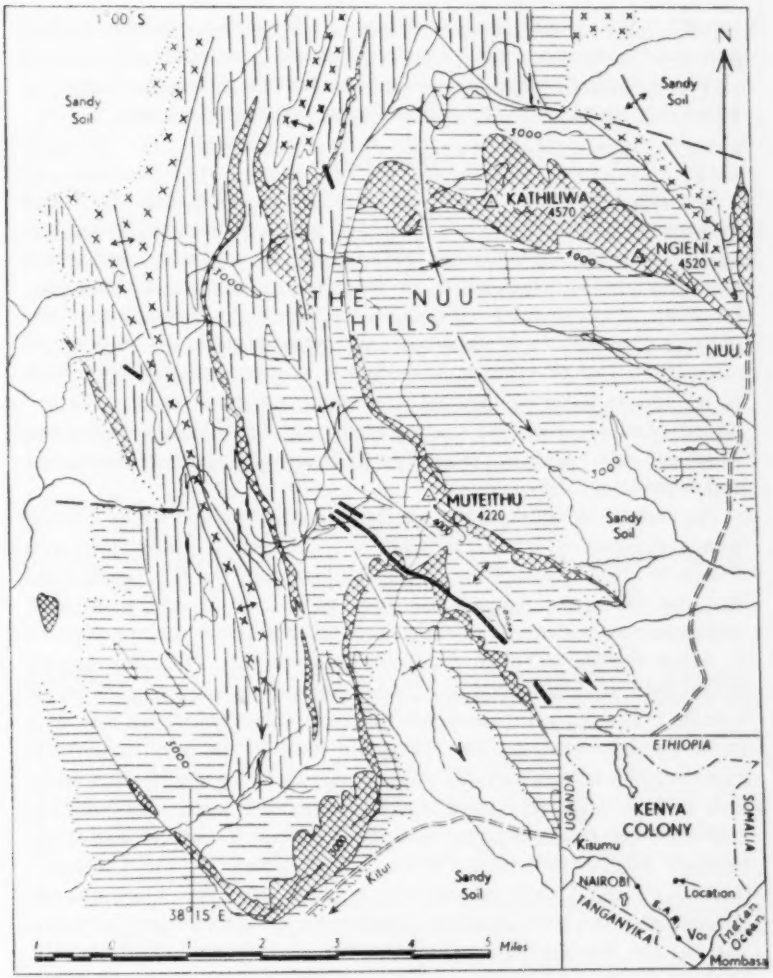
(1) Banded sillimanite-garnet-biotite gneisses are progressively feldspathized, biotite-rich folia being replaced by microcline and oligoclase whilst quartzose bands together with their contained sillimanite resist feldspathization, and ultimately remain enclosed in an otherwise granitoid host (Plate I, fig. 1).

(2) Feldspathization of the quartz-sillimanite bands begins and they are increasingly feldspathized until they break up into irregular sub-rounded bodies of varying size which preserve the same direction of foliation as the neighbouring less altered sillimanite gneisses (Plate I, fig. 2).

(3) The quartz-sillimanite bodies are further reduced in size and become well-rounded. At the same time concordance of fabric between neighbours is lost, indicating the attainment of viscous mobility by the host-rock (Plate II, fig. 3).

(4) The spheroidal bodies are drawn out into ovoids or in extreme cases into sillimanitic streaks, arranged in plastic flow-streams in a granitoid host, producing typical *faserkiesel* gneisses (Plate II, fig. 4).

Throughout these changes the sillimanite occurs as fine fibrolitic needles arranged in wavy threads and films enclosed in granoblastic quartz. It is only found in well-formed prisms where the gneisses have suffered little feldspathization and it would appear that progressive alkali enrichment is accompanied by the conversion to fibrolite, which remains stable until a late stage of dissolution of the quartz-sillimanite bodies when it is finally converted to muscovite or damourite, either by retrogressive metamorphism or by a continuation of potash metasomatism. The white mica so formed produces distinctive patches, clusters, and radial segregations in the granitoid gneisses which, since their origin is clearly demonstrated by field relationships, have been



TEXT-FIG. 2.—Sketch-map of sillimanite migmatites in the Nuu Hills, Kitui, Kenya.

termed " pseudo-sillimanite gneisses ". Almandine garnets riddled with quartz inclusions sometimes occur in the quartz-sillimanite ovoids and have similar optical and physical properties to those contained in adjacent non-migmatitized sillimanite-garnet-biotite gneisses.

Discussion

Existing knowledge of the distribution of sillimanite in Kenya indicates that the mineral has formed in pelitic gneisses of appropriate composition over a great area of metamorphic terrain and does not show a relative concentration within or about granite centres. It is notable, however, that whereas sillimanite occurring in non-migmatitized gneisses and schists is inconspicuous, that engulfed in regions of migmatitization or syntexis immediately attracts attention by reason of its unique habit of forming *faserkiesel*, the pure white " silken " texture of which provides a sharp contrast with the enclosing migmatites which are often pink in colour due to both a high microcline content and superficial iron oxidation.

The stability of sillimanite in the Basement System gneisses of Central Kenya suggests an overall increase in metamorphic grade from west to east in this portion of the Mozambiquian belt, but it is emphasized that the sillimanite isograd has been plotted as an approximation, and as more detailed information becomes available it may be possible to define regions in which the lower grade indices, staurolite, garnet, and biotite, are characteristic. This is particularly likely since both the kyanite and sillimanite zones are of great width by comparison with those demonstrated in other orogenic belts. The sillimanite zone measures at least one hundred miles across the strike, whilst the kyanite zone of South-Central Kenya is of even greater extent. This contrasts with the steep metamorphic gradients of (i) the Caledonian belt of the Scottish Highlands where the crystalline schists of the Dalradian and Moine series show an increase in grade from the chlorite to the sillimanite zones over distances which vary between 30 and 80 miles, and (ii) the Appalachian geosyncline where, in New York State, the Hudson River slate shows a change of metamorphic grade from the biotite to the sillimanite zones over a distance of only 15 miles. The comparatively wide front over which the Mozambiquian belt of Kenya exhibits a high grade of regional metamorphism is possibly determined by the greater depth to which the Basement System has been eroded consequent upon a closer approach to isostatic equilibrium than that exhibited by the younger Caledonian axes of the British Isles and the eastern United States.

Sillimanite formation over a large province and in a zone which parallels the Mozambiquian orogenic trend has evidently been caused by the mineralogical response of aluminous sediments to advancing

metamorphism, kyanite giving way to sillimanite under extreme regional stresses and temperatures. Where quartz-fibrolite bands are preserved in granitoid gneisses they bear witness to the transformation in place of the enclosing rocks from foliated biotite-rich gneisses to feldspathic granulites. The surviving sillimanite-bearing bands are always quartzose and resemble thin quartzites in their resistance to granitization. They show no evidence of disturbance by intrusion and their final disruption, together with the ultimate moulding of the sillimanite bodies derived from them was only achieved where the host-rock had reached a plastic condition. In Central Kenya this remarkable ability of the sillimanite-quartz combination to survive in areas of syntectonic granitization makes it unnecessary to seek the source of the sillimanite outside the pelitic gneisses of the Basement System.

In conclusion I have to thank Professor R. M. Shackleton for introducing me to the subject, and Dr. W. Pulfrey for kindly reading the manuscript and making many helpful suggestions.

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EXPLANATION OF PLATES I AND II [1]

FIG. 1.—Stage I—Granitized sillimanite gneiss, showing five almost vertical quartz-sillimanite bands in granitoid gneiss. Plane of foliation parallel to that in neighbouring sillimanite gneisses.

The exposure is *in situ*, note continuation of bands below hammer.

FIG. 2.—Stage II—Irregular quartz-sillimanite bodies in granitoid gneiss. The foliation of the original sillimanite gneiss is not entirely obliterated. Note variation in size and shape of individual bodies.

FIG. 3.—Stage III—Quartz-sillimanite spheroids in granitoid granulite. Note random distribution and absence of large bodies similar to those in Fig. 2.

FIG. 4.—Stage IV—*Faserkiesel* gneiss. Attenuated quartz-sillimanite ovoids arranged in viscous flow-streams in granitoid host rock.

[1] Figures 1–4 (Plates I and II) are published in "The Geology of the Kitui District", by L. D. Sanders. Report No. 30. *Geol. Surv. Kenya.*

FIG. 1.

FIG. 2.

SILLIMANITE MIGMATITES, KITUI, KENYA.

FIG. 3.

FIG. 4.

SILLIMANITE MIGMATITES, KITUI, KENYA.

The Carboniferous Rocks of Foynes Island, County Limerick

By Frank Hodson

Abstract

The lithological and faunal successions of some 1,150 feet of Carboniferous beds exposed on Foynes Island, County Limerick, are described and shown to be of Namurian Age. The stratigraphical position of *Reticuloceras subreticulatum* (Foord) and *Homoceratoides divaricatus* (Hind) has been ascertained by collecting from the type localities on the island. The palaeogeographical implications of the succession are discussed.

Introduction

THE village of Foynes lies on the south bank of the River Shannon in North County Limerick. Foynes Island is permanently separated from the mainland by some 300 yards of the tidal waters of the river. The main geological interest of the island is centred around the lowest Carboniferous beds exposed, since these contain well-preserved goniatites which permit the beds to be accurately zoned and compared with beds of similar age elsewhere in Europe. Moreover, the type localities for two goniatite species—*Reticuloceras subreticulatum* (Foord) and *Homoceratoides divaricatus* (Hind)—are situated on the island and it is important to determine the exact stratigraphical horizon from which the type material of these species was collected.

Previous Research

The Foynes area is represented on the Irish 1 inch to 1 mile Geological Survey Map, Sheet 142, and described in the corresponding sheet memoir (Kinahan and Foot, 1860). On the original edition of the map (1859) and in the memoir, the whole of the strata on Foynes Island were referred to the "Coal Measures". In the revised edition of 1882, the lowest beds were assigned to the Yoredale Series and the remainder to the Millstone Grit. Hind (1905) rightly questioned the correlation of the lowest beds with Phillips's Yoredales and referred them to his own Pendleside Series. But these terms are becoming obsolete as stratal units, and the beds are not in fact the homotaxial equivalents of those outcroping on the western side of Pendle Hill in Lancashire, which are Viséan and basal Namurian. All the strata exposed on Foynes Island belong to the Millstone Grit Series (Namurian).

Geological Structure

The main feature of the regional tectonics of North County Limerick as well as of West County Clare to the north, is a regional tilt to the south-west. Approximately at right angles to the strike of this tilt

is that of a series of minor folds whose intensity increases from north to south, i.e. along the line of approach to the Hercynian fold-belt of Southern Ireland. In North-West County Clare, the minor folding is subordinate and so gentle that for practical purposes the beds may be regarded as dipping gently to the south-west (Hodson, 1954). In the area west of Ennis, Co. Clare, the minor folds are more important having the form of open folds with an amplitude of 200 feet to 300 feet and a width of a few hundred yards. The south-westerly tilt manifests itself as the pitch of this minor folding. Still further south, in the area forming the subject of this paper, the folding is sharper, with the crests of the folds not infrequently broken. These small but intense folds are a feature of the district and well displayed on the island and adjacent southern shore of the Shannon estuary. A section opposite the quay at Foynes village shows this tectonic style particularly well. The beds, intensely disturbed to the point of development of cleavage, are broken at the crest of a sharp anticlinal fold; but originally contiguous beds are displaced only a matter of inches. This can be demonstrated by following the faunal horizon, only a few inches thick, containing *Ht.* aff. *prereticulatus*, over the break. Elsewhere the throw is greater, but rarely seems to reach a magnitude consistent with the stratal disturbance which accompanies it.

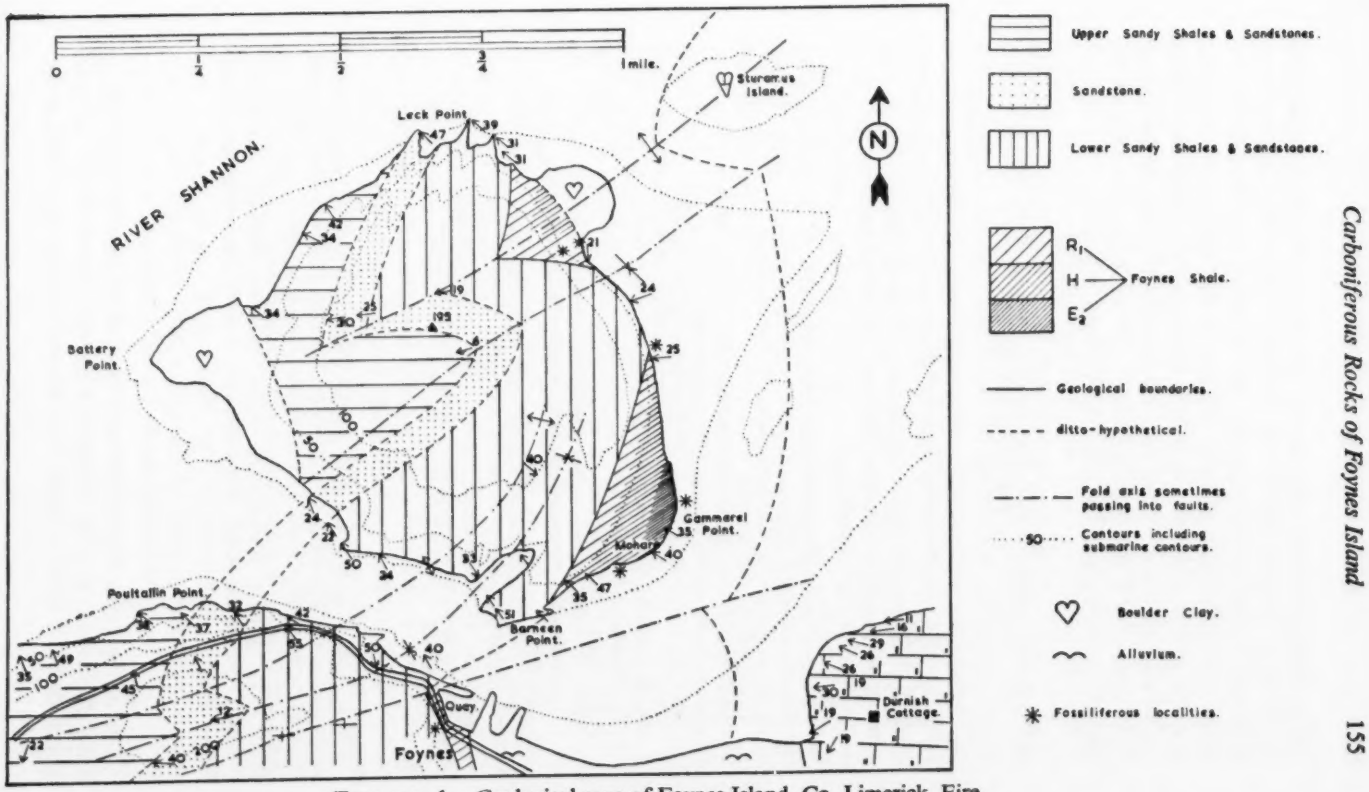
Geological Succession

The thickness of the beds can only be approximately calculated. It seems that there are:—

Sandy shales and sandstones .	about 300 feet
Sandstones	„ 150 „
Sandy shales and subordinate sandstones	„ 400 „
Foynes shales . . .	„ 300 „

That is to say that there are some 1,150 feet of strata, of which about 876 feet lie above the base of the Lower *Reticuloceras* Stage. In the Lisdoonvarna district (Hodson, 1954), North-West Co. Clare, there is an important marine band about 1,000 feet above the base of the Lower *Reticuloceras* Stage which belongs to that Stage also. This band has not been detected on Foynes Island nor do the beds appear to range high enough up the succession for it to be present. Thus by reference to North-West Co. Clare we have indications that the 850 feet of unfossiliferous beds at the top of the Foynes Island succession are to be referred to the Lower *Reticuloceras* Stage of the Namurian.

The following is a measured section on the S.E. corner of the island (Text-fig. 2). The junction of the Upper *Eumorphoceras* Stage (Arnsbergian Stage) and the *Homoceras* Stage (Sabdenian) cannot be determined precisely, but is here provisionally assumed to occur at the



TEXT-FIG. 1.—Geological map of Foynes Island, Co. Limerick, Eire.

top of the platy shales. This would mean that the E_2 Zone, incomplete at the base, is nearly 200 feet in thickness. The overlying Sabdenian is complete and the junction with the overlying Lower *Reticuloceras* Stage occurs approximately at the top of the *Ht.* aff. *prereticulatus* bed and is thus about 80 feet thick. The upper 26 feet of the Foynes Shales and all the overlying beds on the island belong to the Lower *Reticuloceras* or Kinderscoutian Stage. At Samlesbury, in Lancashire, the Sabdenian is about 300 feet thick (Moore, 1930).

SECTION OF THE FOYNES SHALES BETWEEN GAMMAREL POINT AND BARNEEN POINT, FOYNES ISLAND

	Ft.	in.
Nodular, irregularly bedded, shaley sandstones, and shales	—	—
Shales with thin sandstone ribs (2 in.-8 in.), . . about	6	6
Black shales	8	0
Small bullions with *Reticuloceras subreticulatum*,[1] *Hyphantozyga*? *reticulata* (Brown), and *Posidonia* cf. *lamellosa* (de Koninck)	—	—
Black shales	16	0
Large bullions with *Reticuloceras* cf. *circumplicatile*	—	—
Thinly bedded, black shales	3	0
Lare bullions with *Homoceratoides* aff. *prereticulatus*	—	—
Thinly bedded, black shales	10	0
Bullions with *Hudsonoceras proteum* and *Homoceras smithi*	—	—
Black, thinly bedded shales with nodular bands	30	0
Spherical bullions / Shale / Large lenticular bullions } No fossils found but possibly on horizon of *H. beyrichianum* bed.	1	0
Thinly bedded, black shales	40	0
Unfossiliferous nodule bed	—	—
Platy, very well bedded, rather coarse shales with rare ironstone bands. Become more thinly bedded and fissile at the top	150	0
Shale with *Cravenoceratoides* sp. and *Pseudamusium* cf. *jacksoni* Demanet.	—	—
Platy shales and clay bands	19	0
Shales with *Eumorphoceras bisulcatum* and *Cravenoceratoids*	—	—
Platy shales	23	0
Total	306	6

[1] The authors of the goniatite species mentioned in this paper are:—*beyrichianum* (de Koninck) emend. Haug; *bisulcatum* Girty; *circumplicatile* (Foord); *compressum* Bisat and Hudson; *coronatum* Bisat and Hudson; *divaricatus* (Hind); *henkei* Schmidt; *inconstans* (Phillips); *paucicrenulatum* Bisat and Hudson; *prereticulatus* Bisat; *proteum* (Brown); *pulchellum* (Foord); *smithi* (Brown); *subreticulatum* (Foord); *todmordenense* Bisat and Hudson.

STRATIGRAPHICAL PALAEONTOLOGY

One of the important results from the measurement of this section is the determination of the horizon of the bed which yielded the type specimens of *R. subreticulatum.* It is shown to occur 30 feet above the

Hd. proteum band and to succeed a *R.* cf. *circumplicatile* fauna. The members of the *circumplicatile* stock are variable and it is common to find much variation in collections made from a single band. The lectotype of *R. circumplicatile* selected by Bisat and Hudson (1943, p. 425) is recorded from the " Cliffs of Moher ". The only locality on the Cliffs of Moher whence such fossils might have been collected is at Fisherstreet Bay at the extreme northern extremity of the cliffs. Although it is possible that the lectotype might have come from that locality, it is very doubtful that in fact it did so. Forms resembling it are only a minor element of the *Reticuloceras* fauna there, whereas inland, in the Lisdoonvarna district, two bands separated by about 5 feet of shale and some feet below the lowest beds exposed at Fisherstreet, contain *circumplicatile*-like forms abundantly and it seems likely that Lisdoonvarna, which is also quoted by Foord (1897–1903, p. 202) as yielding this species, is the general locality of the lectotype. These early *Reticuloceras* forms assigned to *R. circumplicatile*, *R. coronatum*, " *R. inconstans* " and allied species indicated to Bisat and Hudson (1943) a zone of *R. inconstans*, which was succeeded by a *R. todmordenense* Zone. Hudson and Cotton (1943, p. 152) relegated these zones to the status of subzones. Thus in Western Ireland, *R. subreticulatum* apparently indicates the *todmordenense* subzone and indeed morphologically it is very closely allied both to *R. todmordenense* and to another Irish species—*R. pulchellum*. I have not yet found the type locality of *R. pulchellum* but it seems probable from what is known of the fossils at the base of the Lower *Reticuloceras* Stage in Western Ireland that this species too will be found to occupy a horizon, which in the Pennines would be assigned to the *todmordenense* Subzone.

Thus it seems clear that the onset of arenaceous sedimentation began in Western Ireland during or at the close of the *todmordenense* Subzone and that above the base of the Lower *Reticuloceras* Stage we can discern two faunas, an earlier one, with widely umbilicate Reticuloceratids with plicate umbilical edges, and a later, much more involute assemblage with plain umbilical edges and fine ornament. It seems that soon after its appearance the genus *Reticuloceras* was differentiated into two stocks which, by migration, alternated, since in places, notably at Roughlee in Lancashire, evolute forms such as *R. paucicrenulatum* are seen to succeed a fauna referred to *R. todmordenense*. In Limerick this reappearance has not yet been detected, but a loose bullion found in a stream at Blake's Bridge, N.W. of Lisdoonvarna, Co. Clare, *above* the *R. subreticulatum* band contained a single specimen of the *R. circumplicatile* group.

Homoceratoides divaricatus was described by Hind (1905) from Foynes. It will be seen from the section that the only occurrence of this genus at Foynes is on the band with *Ht.* aff. *prereticulatus*. There seems

no doubt that the type specimen came from that horizon and I suspect that this species does not differ from *Ht. prereticulatus* so markedly as has been assumed. *Ht. prereticulatus* is variable and the holotype was not found *in situ*. It has therefore been customary, in view of the fact that *Ht. prereticulatus*-like forms range upwards in reduced numbers into the lower levels of R_1, to consider that this variation may have stratigraphical significance and not to identify with the holotype specimens found *in situ* even if departures from absolute identity are small. Hence the main bed yielding *Homoceratoides* of the *prereticulatus* gens, which occurs near the top of the *Homoceras* Stage has a fauna designated *Ht.* aff. *prereticulatus*. Now large specimens of *Ht.* aff. *prereticulatus* have the flat ribs supposed to be the prerogative of *Ht. divaricatus*. Moreover, since it is virtually certain that the type of the latter came from near the top of the *Homoceras* Stage it seems that the two species, even if distinct, overlap in the lower part of their ranges. It may be that distinction can be maintained in that the flat ribs appear late in *Ht. prereticulatus* and early in *Ht. divaricatus* but the whole group stands in need of revision.

Work in Western Ireland has shown that the "*inconstans*" fauna is not the first of the Reticuloceratids since a form near *R. compressum* is the first of this genus to appear associated with *H. henkei* and a species of *Homoceras* provisionally called *H.* sp. nov. *A.* by Bisat and Hudson (1943). This fauna has not been detected on Foynes but may be expected to lie between *Ht.* aff. *prereticulatus* and *R.* cf. *circumplicatile*.

Comparison of the Foynes Section with North-West County Clare

The picture of the Middle Carboniferous beds of Western Ireland which is emerging from recent studies involves three main phenomena:—

(1) A Mid-Carboniferous (Sudetian) unconformity the magnitude of which varies from place to place, possibly in a systematic manner.

(2) Resumption of sedimentation in basins or troughs against the sides of which higher beds overlap the lower.

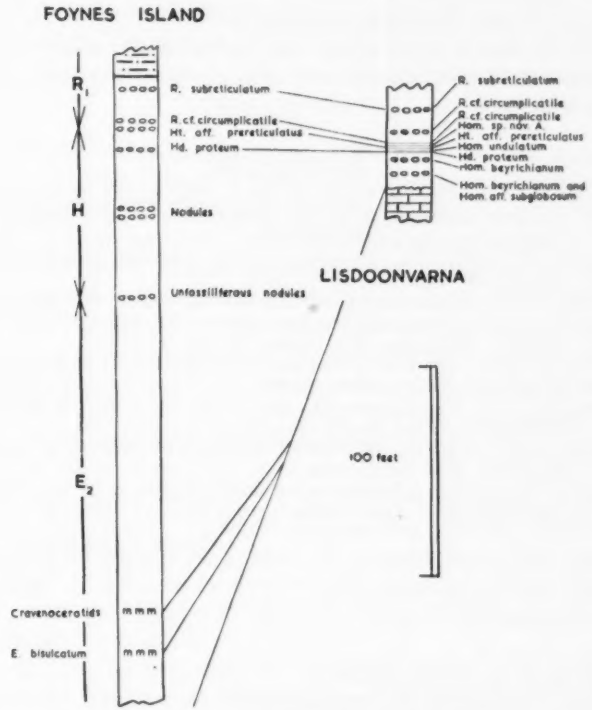
(3) Thicker deposition in the central parts of the basins or troughs.

It is not yet known what were the relative contributions of folding and erosion to the formation of these Mid-Carboniferous depressions.

Lisdoonvarna, in North-West Co. Clare seems to have lain near the northern margin of a trough and Foynes somewhere near the centre. The southern edge of the trough seems to have lain near Ballagh, west of Newcastle West, Co. Limerick, 13 miles to the south of Foynes.

Features of the sedimentation in the contrasted northern region and central parts of the trough are shown in Text-fig. 2.

As regards item (1) above, it could be that there is no unconformity at Foynes since the sections seen do not display the junction of the Carboniferous Limestone and the overlying beds. There seems to be room for some 200-300 feet of strata between the lowest beds on Foynes Island and the Carboniferous Limestone on Sturamus Island.[1]



TEXT-FIG. 2.—Comparsion of the Namurian beds of Foynes Island and Lisdoonvarna.

This thickness, however, is unlikely to contain the remainder of E_2, the whole of E_1 and P_2, even if P_1 is of limestone facies.

With respect to (2), the overlap may not be as simple as shown in Text-fig. 2. It is possible that a close study of the intervening areas will reveal that the main trough is composite.

[1] On the Irish Geological Survey Sheet 142, this island is mapped in error as Millstone Grit.

Point (3) is brought out by a comparison of the thicknesses of beds between homotaxial horizons in the two areas. There are only 2 feet of shales between the *Hd. proteum* band and the *Ht.* aff. *prereticulatus* band at Lisdoonvarna whilst there occur 10 feet at Foynes. Between *Hd. proteum* and *R.* cf. *circumplicatile* near Lisdoonvarna occur 4 feet of shales whilst at Foynes they are separated by 13 feet of shales. The interval between *R.* cf. *circumplicatile* and *R. subreticulatum* seems to be spanned by about the same thickness of strata in both areas. It appears, that after restricted sedimentation on the flanks of the trough during ages before and including the *Homoceras* Age, a general submergence caused more uniform deposition which prevailed over a wide area.

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The Geometry of the Ben Lui Fold (S.W. Highlands)

By Paul C. Gilmour and Donald B. McIntyre

Abstract

It has been claimed that the hinge of one of the two major recumbent folds of the S.W. Highlands is exposed near Ben Lui. In this paper it is claimed that the form of the outcrops permits the existence of this recumbent fold only if the fold-axis plunges towards the south-west. Evidence is given that the plunge is in fact towards the west, and on this basis a profile has been constructed to illustrate the observed geometrical relationships of the rocks.

Introduction

A SUPPOSED stratigraphical succession has been the basis of most attempts to unravel Highland structures, and it is therefore not surprising that there is sometimes considerable diversity of interpretation. The stratigraphical method has proved adequate for the study of gently folded, fossiliferous rocks, but it is founded on certain assumptions which are not likely to be valid in a metamorphic complex. Hitherto it has not been sufficiently realized that if folded rocks outcrop, their shape can be determined from purely geometrical considerations; the stratigraphical data should be superimposed on the observed structural framework. The relationship between stratigraphy and tectonics has been well expressed by Argand (1911, pp. 17–18): " The stratigraphic entity, based on material, in no way contradicts the tectonic entity, based on form. They are different things, partially oblique to one another. . . . In certain cases it is possible to recognize the structural forms by using a minimum of stratigraphy, and then to unroll them to find out, so far as in possible, how the material studied in detail by the stratigrapher is distributed in the forms recognized by the tectonician " (translated).

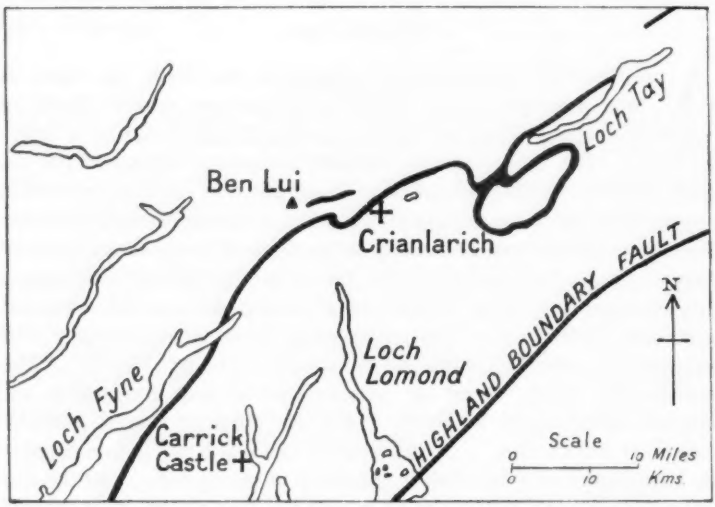
As a result of Bailey's structural synthesis (1922), it is generally recognized (see Wright *et al*, 1922) that the S.W. Highlands consist of three great nappe complexes, and that in one of these, the Iltay Nappe, there are two major recumbent folds; these are the Carrick Castle and Ben Lui (Laoigh) folds, named after the localities where the respective hinges are supposed to be visible (Text-fig. 1). In the present paper an attempt is made to analyse the observed geometric relationships of the rocks in the neighbourhood of the Ben Lui hinge. During the past two years the Carrick Castle area has been under investigation, and the results will be given in another paper.

Bailey's Interpretation

The relationship between the published maps (one-inch, Sheets 45

and 46) and Bailey's sections (see especially Bailey, 1938, fig. 12, reproduced in the Grampian Highlands Regional Guide, 1948, fig. 7A), implies a plunge towards the south-west in the Ben Lui region. On the basis of these published maps, we have constructed a profile of the critical region using an assumed plunge of 15° towards the south-west (Text-fig. 3A). The fold appears as a large recumbent structure closing towards the north-west.

For many miles to the east of Ben Lui, and particularly in the region of Loch Tay, the rocks are folded into a series of gentle antiforms



TEXT-FIG. 1.—Locality Map. Outcrop of Loch Tay marble shown.

and synforms which extend over a wide area; this is the well-known " Loch Tay flat belt ". Bailey has assumed (1922, fig. 4) that this flat belt is the upper limb of the Ben Lui fold, i.e. the limb joining the Carrick Castle and Ben Lui closures, but it must be emphasized that no one has claimed to have followed any horizon around both hinges. Moreover, Bailey has used this assumption in order to draw certain otherwise hypothetical closures on sections through ground further to the east (e.g. Regional Guide, 1948, fig. 7B). If even part of the flat belt belongs to the upper limb of the Ben Lui fold, there must be an axial culmination, immediately to the east of Ben Lui, of sufficient magnitude to bring the upper limb down to the present topographic surface; the existence of such a culmination has never been demonstrated.

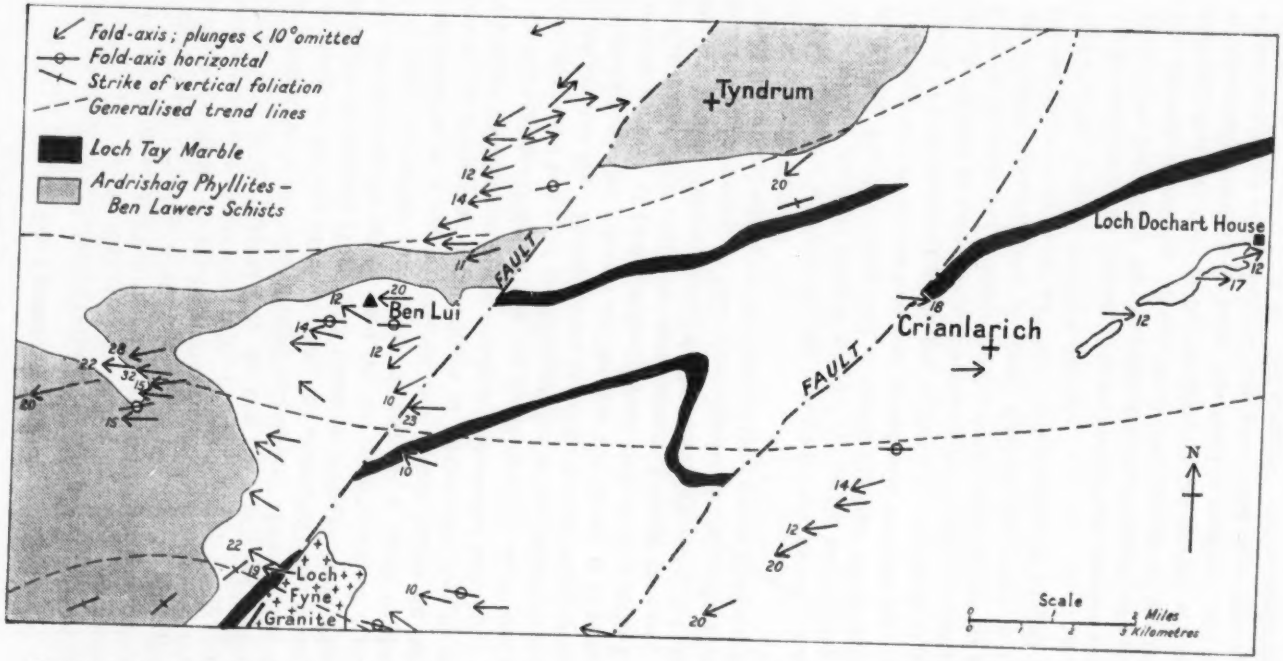
The Corrected Profile

The profile described above (Text-fig. 3A) is hypothetical in so far as the orientation of the fold-axis on which it is based was assumed, and it should be pointed out that no estimate has ever been published of either trend or plunge of the fold-axis in this region. The methods by which the plunge of major structures can be obtained have already been summarized (McIntyre, 1950, p. 428), and it is unfortunate that the data so far published for the Ben Lui region are inadequate for application of any one of these techniques. However, the trend and plunge of the axes of minor folds, and of parallel linear structures, have been determined (Text-fig. 2, based on McIntyre, 1951, Plate 9), and this information can be used for the construction of a profile. It is never altogether satisfactory to rely on a single method of determination of a major fold-axis, but in this region we have at present no alternative; accumulation of further data may of course necessitate modification of the conclusions presented here.

In the neighbourhood of Ben Lui the folds trend nearly east-west; this unexpected fact is of great importance in the geometric analysis of the Ben Lui fold. Further, there is a definite axial culmination near Crianlarich, so that whereas on Ben Lui the plunge is at about 15° towards the west, at Loch Dochart House, three or four miles E.N.E. of Crianlarich, it is about the same amount towards the east. Since the data used in construction of the first profile (Text-fig. 3A) are thus found to be erroneous, we have constructed a second profile (Text-fig. 3B) of the critical region on the basis of the average observed plunge of 15° towards the west.

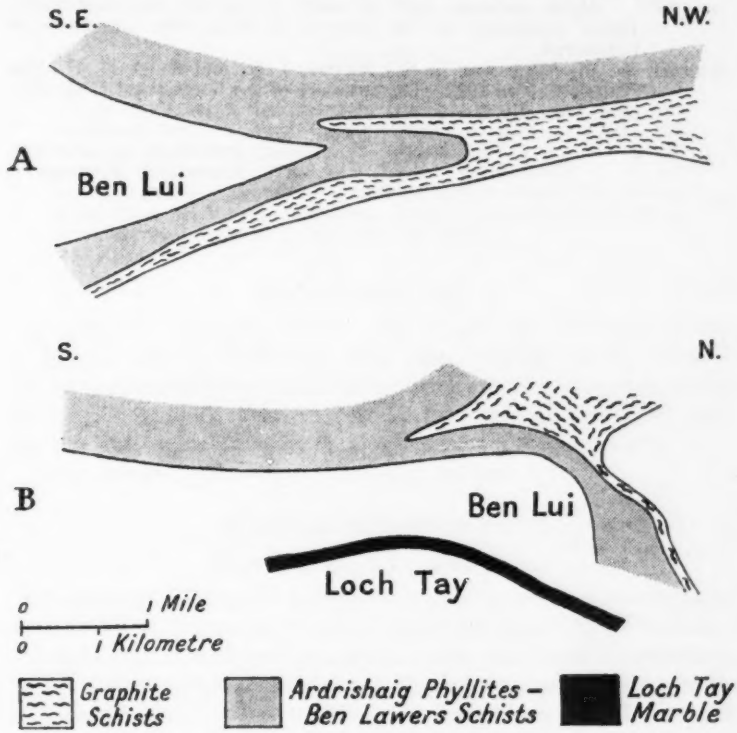
The difference between the two profiles is very striking, and it is clear that the structure hitherto pointed out on the maps as the hinge of the Ben Lui recumbent fold is merely the crest of an antiform; if the supposed recumbent fold does indeed exist, its hinge has yet to be found. To the west and south-west of Ben Lui, and again to the east and north-east of Crianlarich, the plunge must carry the hinge, if it exists in the structural horizons shown on the profile, below the present topographic surface, and it seems unlikely that there is a hinge exposed between these two localities. The existence of a major recumbent fold has certainly not been proved.

The antiform which enables us to see most deeply into the structural units of the flat belt, is the one running along the length of Loch Tay. Our present knowledge of the trend and plunge of the fold-axes indicates that the crest of the antiform in the marble at Loch Tay is structurally immediately below the Ben Lui antiform, and not well to the south-west of the Ben Lui hinge as would have been supposed had the trend been N.E.–S.W. The apparent relative positions of the



TEXT-FIG. 2.—Map showing trend and plunge of observed fold-axes, and of parallel linear structures, in the Ben Lui region.

Loch Tay and Ben Lui antiforms are shown on the profile (Text-fig. 3B), and it will be seen that they are probably one and the same structure. If this is indeed the case, that part of the flat belt which is exposed to the north of Loch Tay must be structurally to the north of the Ben



TEXT-FIG. 3.—A. Profile constructed using an assumed plunge of 15° towards the south-west.
B. Profile constructed using the observed plunge of 15° towards the west. The apparent position of the Loch Tay antiform has been determined by consideration of the form of the longitudinal section.

Lui crest. It can therefore be concluded that our present knowledge of the geometrical relationships of the rocks is opposed to the view that a major recumbent fold exists in the Ben Lui region.

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Idosocrinus gen. nov. and other Crinoids from Thornton Burn, East Lothian.

By James Wright

(PLATE III)

Abstract

The new genus *Idosocrinus* is proposed for a remarkable type of crinoid occurring in the Thornton Burn section of the Calciferous Sandstone Series (Lower Carboniferous) of East Lothian, and two species are recognized. In general habitus the new genus resembles *Phanocrinus* Kirk, but differs in the character of the left and right posterior primibrachs, which extend outward from the cup in the form of strongly developed spines. Two new specimens of *Anemetocrinus wilsoni* Wright are also figured.

Idosocrinus gen. nov.

A SMALL inadunate crinoid with saucer- or bowl-shaped cup and normal (primitive) anal area ; PBrBr single, axillary, supporting two unbranched arms in each ray, but left and right posterior PBrBr differentiated from the others by extending outwards from the cup as long and strongly developed spines ; column round.

Type species : *Idosocrinus bispinosus* sp. nov.

Idosocrinus bispinosus sp. nov.

Plate III, figs. 1, 2 ; Text-fig. 1.

This species conforms to the generic description with special emphasis on the cup which is markedly saucer-shaped and rather flat on the base ; the IB circlet is small and invisible in side view but well seen from below where the IBB extend slightly beyond the column socket which is indented and forms a shallow pit ; lumen small ; BB and RR moderately large ; column round, alternating ; PBrBr single, axillary, supporting two rami of quadrangular SBrBr with more or less parallel sutures ; left and right posterior PBrBr strongly spiniferous.

Holotype.—J. Wright, No. 2542 (Plate III, figs. 1, 2 ; Text-fig. 1).

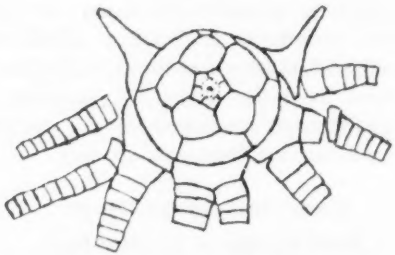
Locality.—Thornton Burn, East Lothian.

Horizon.—Calciferous Sandstone Series.

Dimensions of Holotype.—Diameter of cup, 10·5 mm. ; height of cup, estimated, 5·5 mm. ; length of spines on left and right posterior PBrBr, 6·7 mm. ; length of column preserved, 24 mm.

Remarks.—The holotype is the only specimen so far found at Thornton Burn. It consists of a flattened crown with the rays splayed out from the cup which is lying with the dorsal surface upward. The arms are all incomplete. A short portion of the column is also preserved, but the proximal columnals next the cup are missing,

and the highest preserved part now abuts against and partly hides the anal plates of the cup. In the photograph, Plate III, figs. 1, 2, the anal plates are at the bottom of the cup so that the true orientation of the crown is that shown in Text-fig. 1. Although the anal region is partly hidden it is clear that it is of the three plate primitive type. The cup itself is comparatively flat and saucer-shaped with small IBB. The distinctive feature of the holotype, however, is the strongly spinose left and right posterior primibrachs. When the specimen was discovered the presence of these spines was not expected, since they and the other primibrachs and arms were buried in the shaly matrix and were only revealed when the specimen was cleaned. Apart from the spiniferous primibrachs, the cup and arm characters do not seem to differ greatly from such a genus as *Phanocrinus* Kirk, which is represented in large numbers in the Scottish Lower Carboniferous (Seafield Tower Limestone and its equivalents) by *P. calyx* (McCoy),



TEXT-FIG. 1.—*Idosocrinus bispinosus;* drawing of the holotype as it lies in the shale but with columnals removed from the anal plates of the cup. × 1½.

and in the underlying Ardross Limestone in Fife by *P. ardrossensis* (Wright). So far as the writer is aware no species of crinoid has hitherto been found in British Carboniferous rocks in which the primibrachs bear long spines. It is true that in at least one Scottish species (*Phanocrinus stellaris* (Wright)) the primibrachs are spiniferous but the spines are very short (Wright, 1951, pp. 98–9, pl. xviii, fig. 26). Long spiniferous primibrachs are common in some American genera (*Delocrinus*, etc.). In these forms, however, all five primibrachs may be spiniferous, not two only as in the present form. In the holotype it is clear that the three normal primibrachs resting on LAR, Ant.R, and RAR supported two unbranched arms and it is assumed that the spiniferous primibrachs resting on LPR and RPR also supported two arms of the same character ; but there is an element of doubt about this. In the holotype as preserved it is evident that a normal arm is given off from the inner shoulders of left and right posterior primibrachs, but there is no trace of an arm on the outer

shoulders of these plates. Of course, it has not been possible to uncover the distal faces of the spiniferous primibrachs without risk of seriously damaging the specimen, but judging from the left posterior PBr which is still undisturbed on LPR and proximally is more developed on the inside than on the outside, it seems probable that the outer arms (if any) were narrower and shorter. Only more and better preserved specimens can decide this point.

Idosocrinus tumidus sp. nov.

Plate III, fig. 3

Cup markedly bowl-shaped, with considerable part of IBB extending beyond column socket and just visible in side view ; anal area normal with large RA ; arm characters and spiniferous primibrachs presumably the same as in previous species.

Holotype.—J. Wright, No. 2533 (Plate III, fig. 3).

Locality.—Thornton Burn, East Lothian.

Horizon.—Calciferous Sandstone Series.

Dimensions of Holotype.—Diameter of cup, posterior to anterior, 9·8 mm. ; greatest width from outer angles of LPR and LAR to outer angles of RPR and RAR, 11 mm. ; height of cup, 6 mm. ; length of spine on left posterior PBr, 6·7 mm.

Remarks.—The holotype consists of a cup with the left posterior primibrach in position, although slightly displaced, and a few of the inside arm plates of left posterior ray preserved. The specimen was previously referred to *Phanocrinus ardrossensis* (Wright, 1952*a*, p. 324, pl. xiii, fig. 8). Its cup characters certainly differ little from that species. The discovery of the previous species, however, led to a closer examination of the specimen and further cleaning now shows that the left posterior primibrach is spiniferous and similar in character to that seen in *Idosocrinus bispinosus*. Although this is the only primibrach which is preserved it seems reasonable to assume that the right posterior primibrach is also spiniferous and the other arm characters similar to those of *I. bispinosus*. The specimen therefore is now considered to be a distinct species of *Idosocrinus* differing chiefly from *I. bispinosus* in the more rounded and bowl-shaped nature of the cup and the larger IB circlet. Without the spiniferous left posterior primibrach this cup would normally be taken for an example of *Phanocrinus ardrossensis*, a species which apparently does occur at Thornton Burn as is evidenced by a rather crushed crown found some time ago (Plate III, fig. 4). This specimen shows no trace of spines on the right posterior PBr which is in position. While it is clear that the present species differs from *I. bispinosus* in the shape of the cup it is hoped that better preserved specimens will be found to enlarge our knowledge of the two species.

Anemetocrinus wilsoni Wright

Plate III, figs. 5, 6

Since this species was described, two additional specimens have been found at Thornton Burn (Plate III, figs. 5, 6). Both are excellently preserved and show specially well the character of the arms and pinnules.

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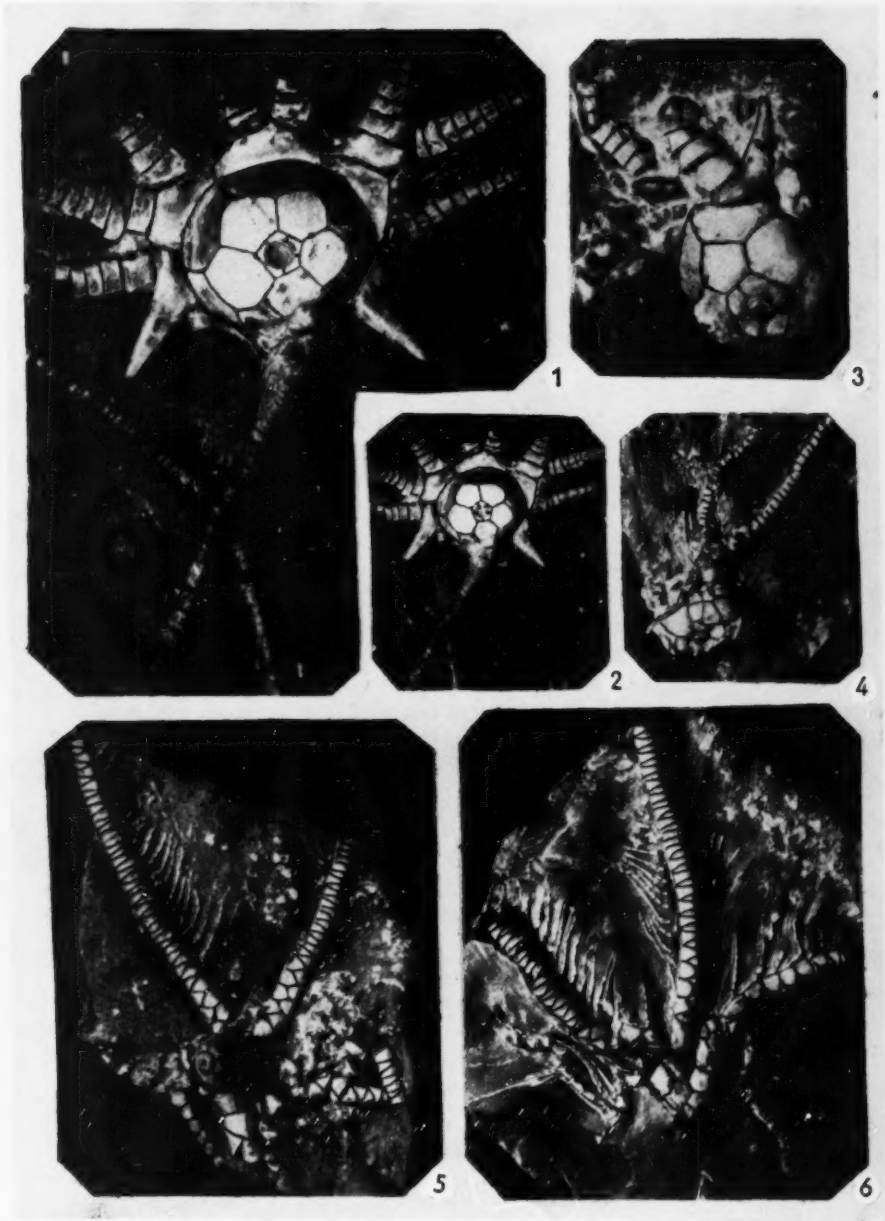
EXPLANATION OF PLATE III

FIGS. 1, 2.—*Idosocrinus bispinosus* gen. et sp. nov., Thornton Burn, East Lothian; holotype; J. W. Coll. No. 2542; the cup is lying with the anal plates at bottom, partly covered by a few proximal columnals and matrix, the column continuing downwards in the photograph. The orientation of the crown is shown in Text-fig. 1. Fig. 1 × 2; fig. 2 × 1.

FIG. 3.—*Idosocrinus tumidus* sp. nov., Thornton Burn, East Lothian; holotype; J. W. Coll. No. 2533; note the spiniferous left posterior primibrach with a few of the inside arm plates preserved. × 2.

FIG. 4.—*Phanocrinus ardrossensis* (Wright)? Thornton Burn, East Lothian; J. W. Coll. No. 2538; a much crushed, incomplete crown, probably belonging to this species. × 1.

FIGS. 5, 6.—*Anemetocrinus wilsoni* Wright, Thornton Burn, East Lothian; two somewhat crushed crowns, showing arms and pinnules; J. W. Coll. Nos. 2536, 2541. × 1.



J. Wright Photo.

CRINOIDS FROM THORNTON BURN, EAST LOTHIAN.

On the Occurrence of *Anthraconauta tenuis* (Davies and Trueman) in North Staffordshire

By J. Myers

Abstract

The finding of *Anthraconauta tenuis* (Davies and Trueman) at Etruria, North Staffordshire, just above the basal limestone of the Newcastle-under-Lyme Beds suggests that the base of the Tenuis Zone, hitherto placed at the base of the Keele Beds, should be brought down to the base of the Newcastle-under-Lyme Beds.

When Davies and Trueman (1927) established the present zonal classification of the Coal Measures their Tenuis Zone was characterized by a new form "*Anthracomya*" *tenuis* associated with "*Anthracomya*" *phillipsii*. In a table of the North Staffordshire succession (p. 248) they showed no upper limit to the Phillipsii Zone, but noted "*Anthracomya*" *calcifera* as typical of the Newcastle Beds. They also said (p. 247) that there was no trace of shells resembling "*Anthracomya*" *tenuis* in Staffordshire.

In a similar table Dix and Trueman (1931, p. 203) showed that there was still no upper limit to the Phillipsii nor any suggestion of the presence of the Tenuis Zone in North Staffordshire. They did, however, record at the base of the Newcastle Beds "*Anthracomya*" *calcifera*, *A*, cf. *phillipsii* and *A.* cf. *tenuis*.

Melville (1947, Table III, opp. p. 308) suggested that part of the Newcastle Beds may belong to the Tenuis Zone and stated (p. 334) that in the absence of typical *Anthraconauta tenuis* it was not then possible to define a base to the zone. The possibility of the Newcastle Beds being part of the Tenuis Zone was suggested by Sir Arthur Trueman in his Presidential Address to the Geological Society in 1947. In this address (1947, p. lxxxi) he says: "The shells formerly called *Anthracomya calcifera*, at the base of the Newcastle-under-Lyme Group, probably indicate the Tenuis Zone."

During the course of a field excursion in the spring of 1952 a visit was made to the marl pit of Metallic Tile Co. (Rowley Bros.), Ltd., Bradwell, near Chesterton, where a fine section of the upper part of the Etruria Marl capped by the lower part of the Newcastle Beds is exposed. The Newcastle Beds were being excavated back prior to extended working of the underlying marls. Among the newly excavated material on the near-by tip much black shale was observed, some pieces of which were crowded with ostracods and fish debris, the latter small and fragmentary. On that occasion no fish band was observed in situ, but a subsequent search located it among some black shales. This band could be followed laterally only for a short distance. The black shales were found to be about 30 to 36 inches above the basal limestone

and in them were many shells of *Anthraconauta* associated with ostracods.

Mr. M. A. Calver of the Geological Survey and Museum kindly examined material from this horizon and noted the occurrence of shells resembling *Anthraconauta tenuis* though smaller than the holotype. The fossils found were as follows :—

Spirorbis sp.
Anthraconauta spat.
Anthraconauta calcifera (Hind).
Anthraconauta aff. *phillipsii* (Williamson).
Anthraconauta cf. *tenuis* (Davies and Trueman), similar to, but smaller than the holotype.
Carbonita pungens (Jones and Kirkby).
Carbonita wardiana (Jones and Kirkby), common.
Fish debris, including the scales of *Rhabdoderma* sp.
Elonichthys sp. and *Rhizodopsis* sp. and Acanthodian spines indet.

A selection of the above fossils is in the Geological Survey's collection under the registered numbers Zi 4984–5000.

Later in the year a brief visit was made to Downing's marl pit at Etruria. Here, as at Bradwell, the Etruria Marl is seen capped by the Newcastle Beds, and again about 3 feet above the basal limestone is a band of black shale, with abundant ostracods and *Anthraconauta*. On one piece of shale, at the top of the band, was found what appeared to be an *Anthraconauta tenuis*, though smaller than the holotype. Its measurements, together with those of the holotype (Davies and Trueman, 1927, p. 236) are given below :—

L	H/L	A/L	
18	39	c.11	α = c. 22° ; β = c. 156° (Etruria)
32	38	13	α = c. 25°; β = c. 150° (Holotype)

[L = Length; H/L = % Height over Length; A/L = % Anterior end over Length.]

A photograph of the specimen was submitted to Sir Arthur Trueman, who expressed an opinion that the lamellibranch was *Anthraconauta tenuis*. This specimen has been presented to the Geological Survey (Reg. No. Zi 3332).

Further material has been examined by Mr. Calver who noted the following in addition to *A. tenuis* :—

Anthraconauta cf. *tenuis* (Davies and Trueman).
Anthraconauta phillipsii (Williamson).
Anthraconauta cf. *phillipsii* (Williamson).
Carbonita wardiana (Jones and Kirkby) abundant.
Rhabdoderma scales.
Acanthodian spines, indet.

This finding of *Anthraconauta tenuis* near the base of the Newcastle Beds at Etruria and of *A.* cf. *tenuis* on a similar horizon at Bradwell suggest that the Newcastle Beds in North Staffordshire are to be referred to the Tenuis Zone.

I should like to acknowledge the help and advice of Sir Arthur Trueman, Mr. M. A. Calver, Professor W. G. Fearnsides, and Professor F. W. Cope, and to thank Metallic Tile Co. (Rowley Bros.), Ltd., and G. H. Downing and Co., Ltd., for permission to visit their marl pits.

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CORRESPONDENCE

LUGEON'S UNPUBLISHED INTERPRETATION OF THE STRATH OYKELL MULLIONS

SIR,—Petrofabric studies by F. Coles Phillips (*Quart. Journ. Geol. Soc.*, xciii, 1937), and a detailed megascopic investigation by Gilbert Wilson (*Proc. Geol. Assoc.*, lxiv, 1953) have clearly demonstrated that the mullions of Strath Oykell are normal to the single symmetry plane of the fabric on all known scales; the mullions are therefore *b*-structures by definition. The recognition of this seems now to be generally accepted. It is therefore desirable to draw attention to the record of a remarkable unpublished interpretation by the late Professor Maurice Lugeon, who appears to have been the first investigator to interpret the Strath Oykell structures in this manner.

In the teaching collection at the University of Lausanne there is a particularly instructive specimen from Strath Oykell. It shows monoclinic folding, and the micas of the pelitic bands are parallel to the axial planes; the fold hinges form longitudinal ribs, and parallel to these there is a lineation caused by the intersection of the micas with the foliation. Last December, through the courtesy of Professor Badoux and Dr. Aubert, I saw the original catalogued description in Lugeon's handwriting:

> " No. 14072. Leptynite micacée de la série des ' Moineschist ' (Précambrien) présentant le *Mullion* ou *Rodding structure* des géologues écossais, soit le résultat d'une pression transversale à la direction et au plongement moyen des couches.
>
> M. Lugeon. 12.ix.1912. R. Oykell."

The specimen was therefore collected at the beginning of the celebrated post-British Association excursion (Dundee, 1912), led by Peach and Horne, on which Lugeon composed his well-known " Chanson du Moine Thrust ". The interest of Lugeon's description of the mullions, written before he had seen the Moine Thrust, is that their interpretation was so obvious to this alpine geologist that apparently he did not realize that these structures were not correctly understood by Highland geologists.

DONALD B. MCINTYRE.

GRANT INSTITUTE OF GEOLOGY,
UNIVERSITY OF EDINBURGH.
27th January, 1954.

RULES OF NOMENCLATURE

SIR,—May I draw the attention of palaeontologists to clause 54 (1) (*a*) of the " Additions to, and modifications of, the Règles Internationales de la Nomenclature Zoologique approved and adopted by the XIVth International Congress of Zoology, Copenhagen, August, 1953 "? This clause directs that where the name of the type genus of a subfamily, family, or superfamily has been changed because it is a junior synonym (whether objective or subjective), the name of the subfamily, family, or superfamily based upon the name of that type genus is not to be changed.

Our colleagues who sacrified their time, energies, and funds in attending the Copenhagen Congress achieved so much that is excellent and put us so greatly in their debt, that it seems ungracious to criticize their decisions. On this particular point, however, there surely must have been sharp division of opinion. The decision would have such unhappy effects in at least molluscan systematics that, if Mollusca are a fair sample, I feel palaeontologists should do all possible to prevent this clause from being incorporated in the new Rules of Nomenclature.

Some of the changes that would be required would produce completely unfamiliar monstrosities, for some family names formed on invalid objective

synonyms have been jettisoned and ignored almost from the moment of proposal, along with the invalid nominal genus. The prospect of family and superfamily names henceforth having to be altered so as to revive and immortalize invalid junior synonyms is as daunting as the prospect of the discreditable hunt that will be started among the literature, to be the first to unearth these corpses for revival.

If all palaeontologists who object to this clause becoming part of the Rules will write to the Secretary of the International Commission on Zoological Nomenclature, Mr. Francis Hemming, 28 Park Village East, Regent's Park, London, N.W. 1, let us hope that our protests may avail. (A copy of this letter is being sent him.) If any systematist feels that in an exceptional case it is desirable to retain a well-known family name based on an invalid synonym it is always open to him to apply for the protection of the Commission on behalf of that name. Otherwise, the Rules surely should state the obvious: namely, that the legitimate name of a family (or subfamily or superfamily) is that which is formed on the valid name of the type genus.

W. J. ARKELL.

SEDGWICK MUSEUM,
CAMBRIDGE.
7th February, 1954.

COMMENTS ON THE CARIBBEAN OLIGOCENE

SIR,—Dr. Eames's attempt (*Geol. Mag.*, xc, 1953, pp. 388–392) to transfer half the Caribbean Oligocene into the Miocene is remarkable for the short list of references. The works of Caudri, Drooger, Grimsdale, Hedberg, Kugler, Olsson, Renz, Vaughan, and Woodring—to name but a few—should surely be considered before claiming flatly that *Miogypsina* indicates a Miocene age, regardless of other considerations.

A regional transgression can be recognized in the West Indies and in northern South America, Ecuador, and Peru. The transgressive beds are marked by the appearance of new faunal elements, which include Chattian-Rupelian molluscs (*fide* Olsson, Rutsch, Woodring, *et al.*), and Oligocene larger foraminifera (*fide* Vaughan and collaborators, Caudri, *et al.*). The genus *Miogypsina* appears in the basal transgressive beds in several countries (Drooger, *et al.*), and its early forms appear to be a direct development from the Lower Oligocene *Rotalia mexicana*. The basal Camana unconformity in Southern Peru is a local example of the regional transgression: the presence of *Miogypsina* (*Miolepidocyclina*) *ecuadorensis* establishes correlation with beds in Ecuador, which themselves underlie thick pre-Aquitanian shales. Hence the basal Camana beds are Oligocene and Eames's claim (op. cit.) of a Miocene age is unacceptable.

Between the time of the mid-Oligocene transgression and the first appearance of faunas of Aquitanian type, the planktonic foraminifera show a well-defined pattern of change and evolution, consistent over the whole mid-American region. *Globigerina dissimilis* survived for a short time. Near its evel of extinction the genus *Globigerinatella* made a short-lived appearance. The *Globorotalia fohsi* clan appeared, with an evolutionary sequence of subspecies, but died out abruptly as *G. menardii* appeared. *Orbulina universa* was preceded by its ancestral form *O. suturalis*.

European paleontologists could make an invaluable contribution to transoceanic Tertiary correlation by following Colom, Grimsdale, and others in recording the ranges of these species in the European Tertiaries.

R. M. STAINFORTH.

C/O INTERNATIONAL PETROLEUM CO.,
TALARA, PERU.
9th February, 1954.

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LAPWORTH, C. 1878. The Moffat Series. *Quart. Journ. Geol. Soc.*, xxxiv, 240–343.

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